Ruminations on jet quenching in context (primarily) of ATLAS measurements

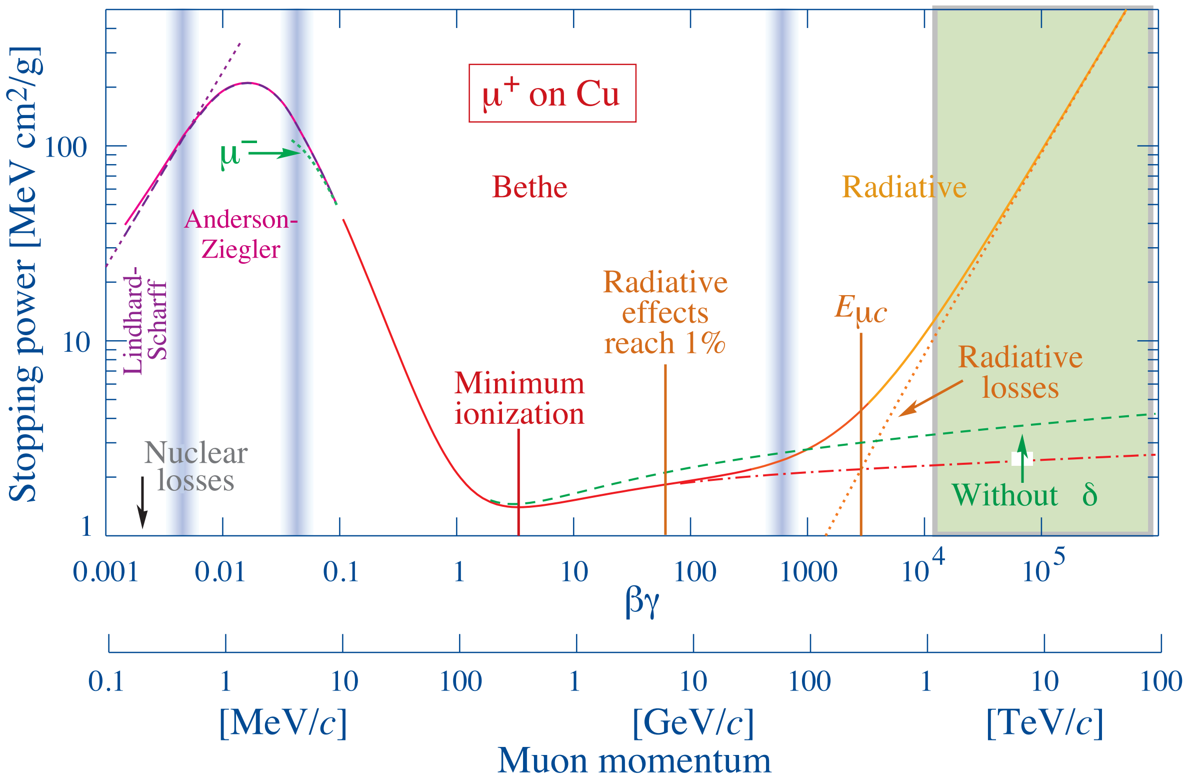
Prof. Brian. A Cole
Columbia University

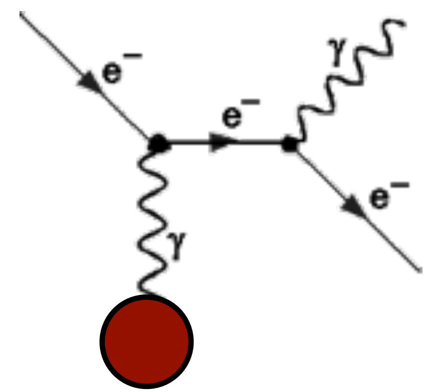
BNL High-pT workshop

Alas, the keynote file for my talk was corrupted and (unusually for me) I have no backup. I will use slides from Aaron's talk at Santa Fe workshop as basis for my talk with a few additions in pdf file.

Jet Tomography

- Often stated goal of jet quenching studies is to use jets to probe the structure of the QGP
- Temptation is often to proceed in strict analogy with QED

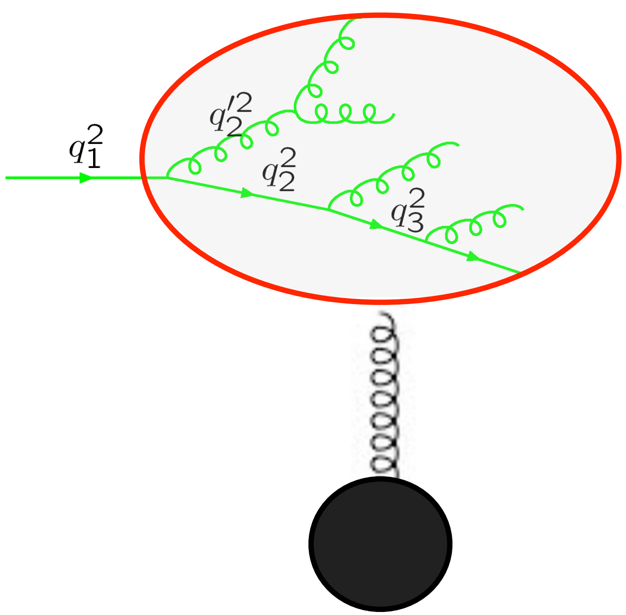




- In QED in <u>radiative regime</u>, interaction characterized by <u>single scale</u> (radiation length)

Jet Tomography

- Know from generations of QCD phenomenology that jets emerge from hard scattering processes with large virtuality and that they radiate copiously as they evolve back on shell
- Pattern of radiation is known as the parton shower
  - Enhancement of higher order radiation (large logs) arising from separation of scales between initial and final jet virtuality
  - Evolution of parton is virtuality ordered
- Jet is a coherent object and emissions are angular ordered



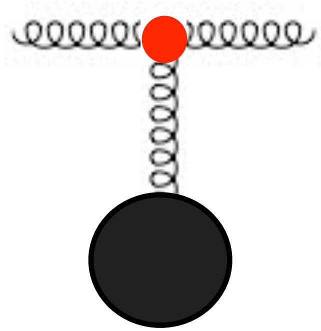
- E-loss not obviously characterized by single scale, probe has hierarchy of scales…
- What is the relationship between these scales and those set by the medium?

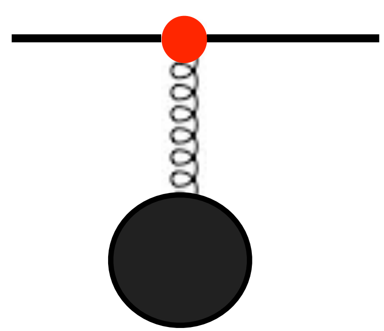
➡ To what extent does medium resolve jet?

- Need to understand this well before phenomenon can be used to “measure” the medium scales

Flavor Dependence of Jet Energy Loss

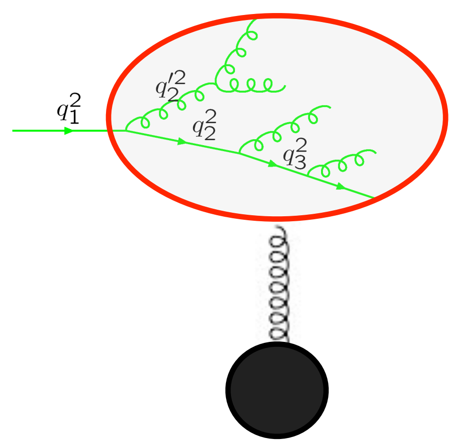
- **Properties of jets, final momentum distribution of hadrons w/in jet, sensitive to whether initial parton is a quark or gluon**
  - **“Gluon jets” wider, less likely to have high z leading fragment and have larger multiplicity**
  - **Distinction is only strict in LO picture (or LO+PS)**
- **May expect gluons to receive 9/4 enhancement in E-loss due to color factor**





Detailed analysis of this in the context of PYTHIA
Cole and Spousta,1504.05169 [hep-ph]

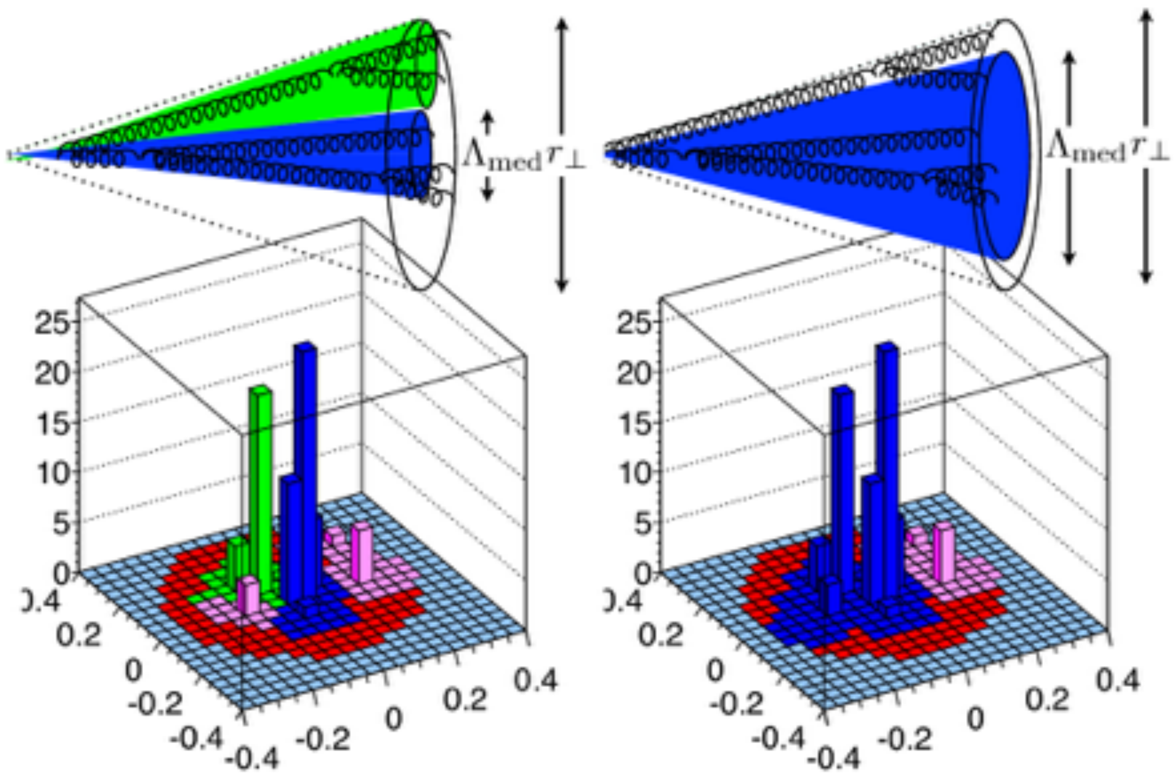
- **But if medium resolves jet how much does initial flavor matter?**



- **Can study this by varying mixture of of *q/g* initiated jets**

Coherence Approach to Quenched Jets

- Recent theoretical advances in coherence based approach
  - Combined effects of vacuum (virtuality and angular ordered) and in-medium (time ordered, angular anti-ordered) cascades
- Medium resolves jets to some scale (Λ_{med})
- Does not see jet substructure on smaller length scales, only total color charge, i.e. coherent substructures

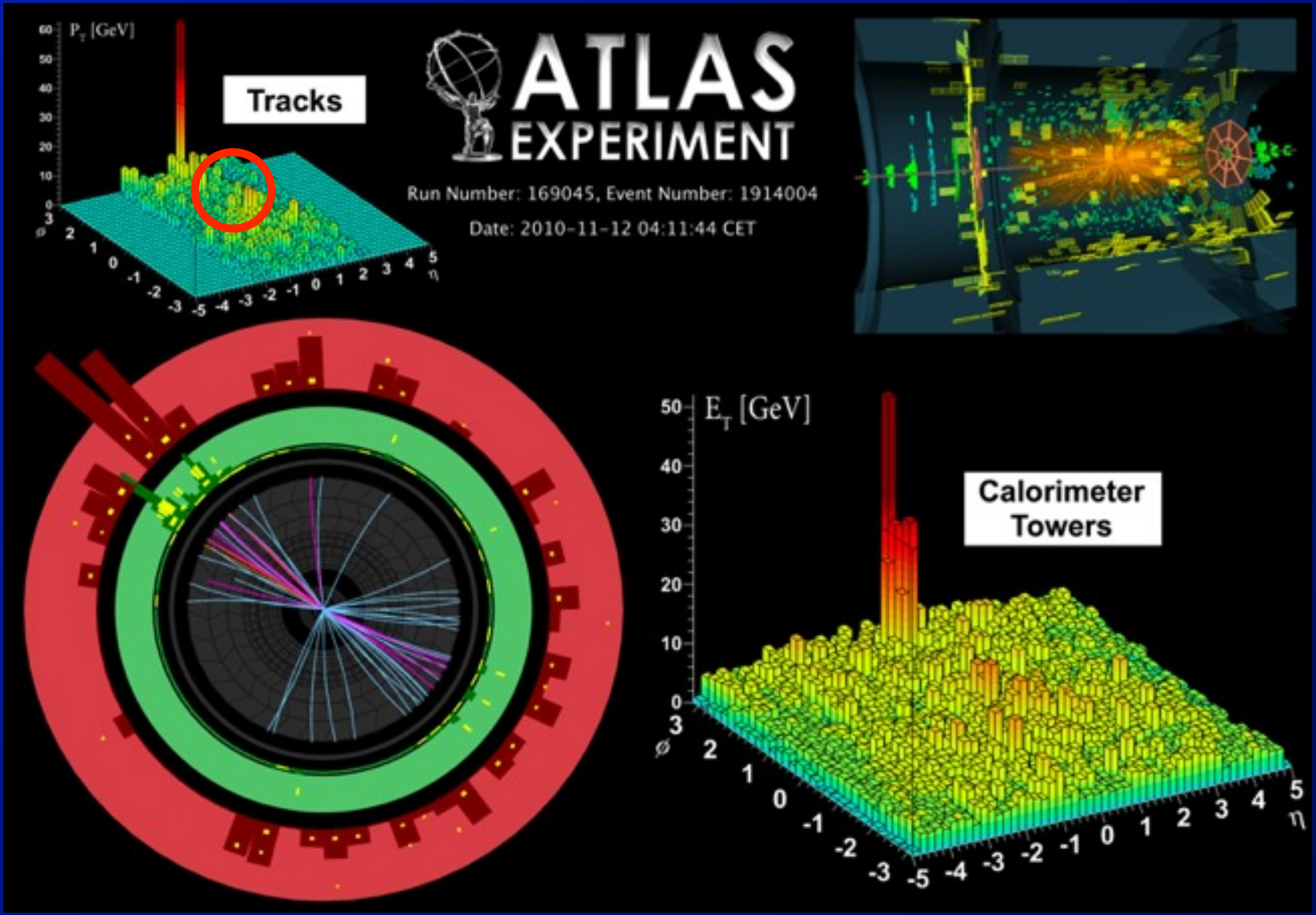


➡ Depending on details of parton shower medium resolves jet into <u>number of effective emitters</u>

- Jets with different parton showers (categorizable by their substructures) are quenched differently

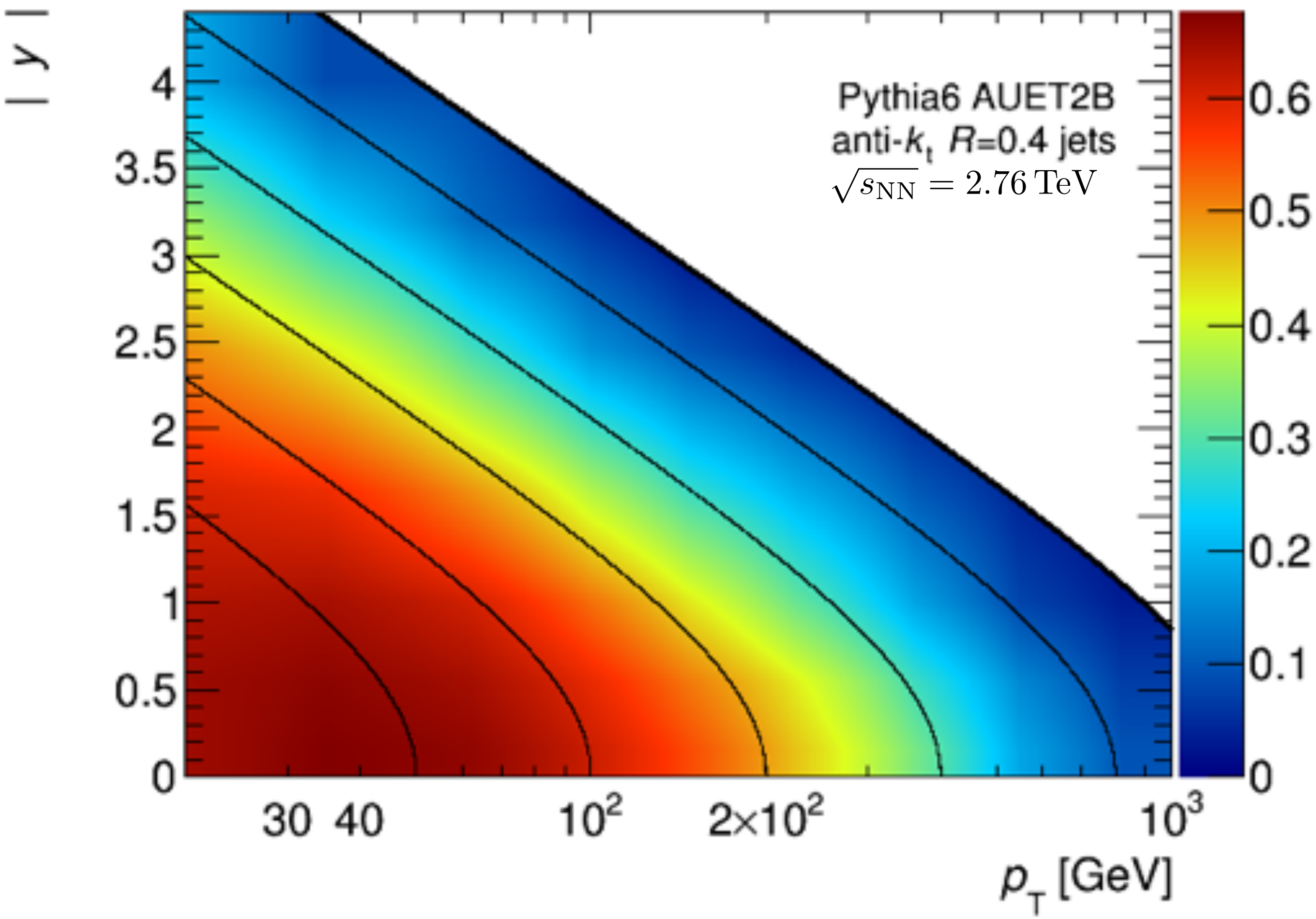
Casalderrey-Solana, Mehtar-Tani, Salgado, and Tywoniuk
Phys.Lett. B725 (2013) 357-360

Example of non-trivial jet structure



Gluon Fractions: Single Jets

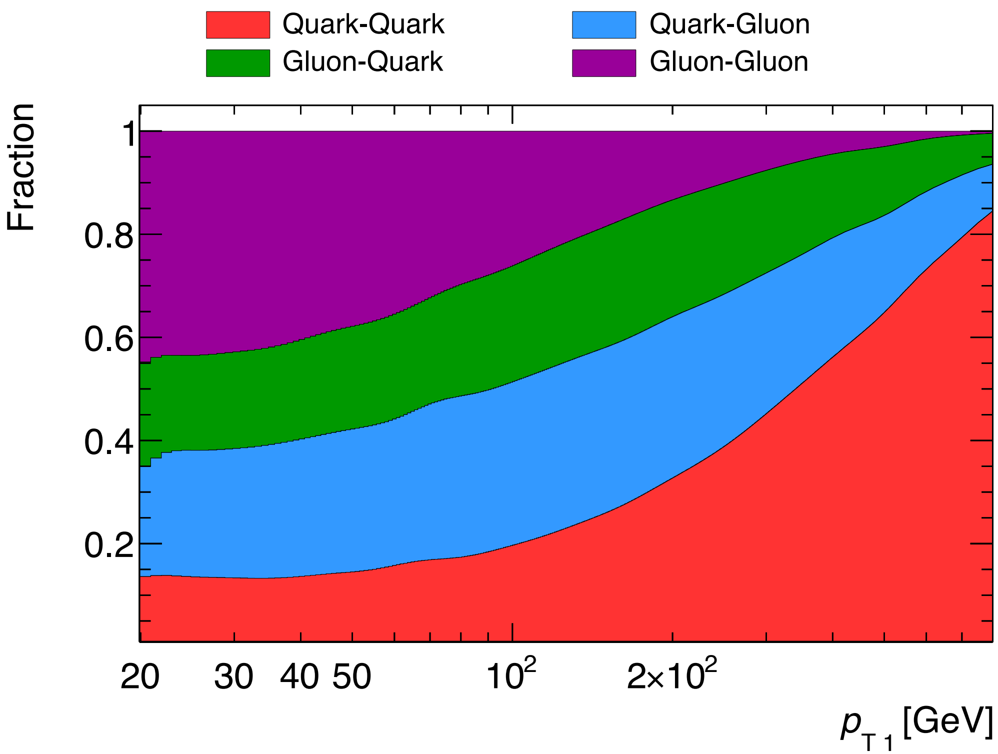
- **Flavor of jet defined to be highest p_T parton w/in R of jet**

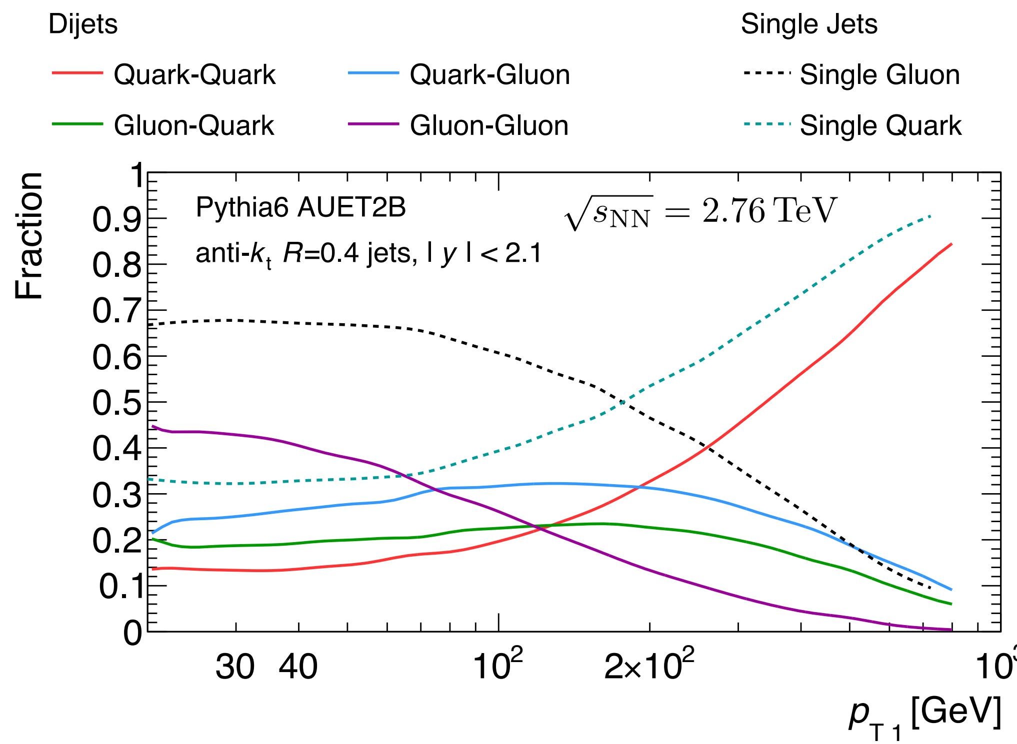


- **Note that PDFs and flavor fractions are only indirectly related**
  - **Fractions extracted from generator which has initial and final state parton showers that may change flavor/kinematics of parton-level jets**

- **Two generators (e.g. PYTHIA and HERWIG) that have different PS implementations will not necessarily give the same flavor fractions even if they use the same input PDFs**
- **Also the *tune* of the generator matters, e.g. α_S used in ISR**

Gluon fractions: Dijets





- Naive expectation, Quark-Gluon configuration expected to show largest asymmetry *on average*

Partonic Fragmentation Functions

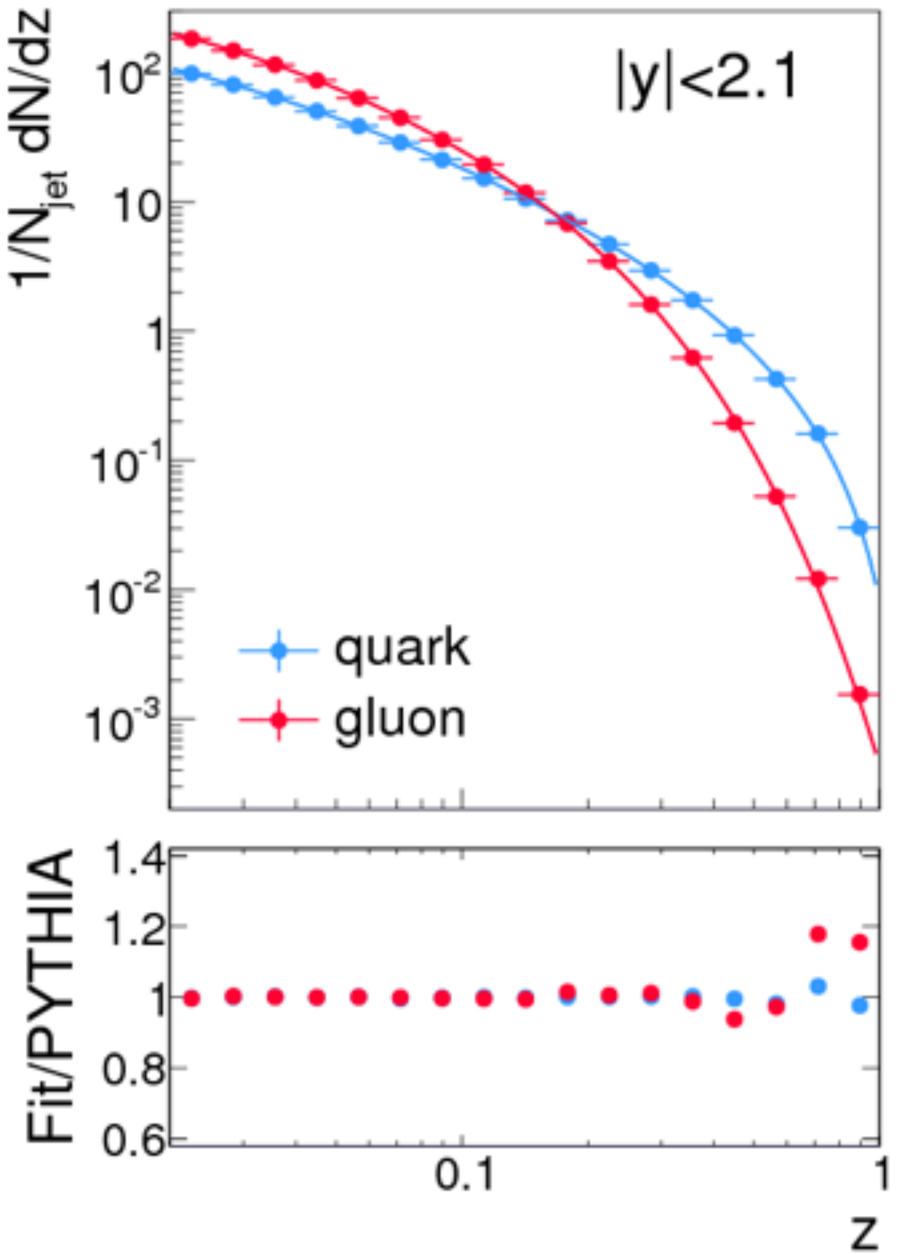
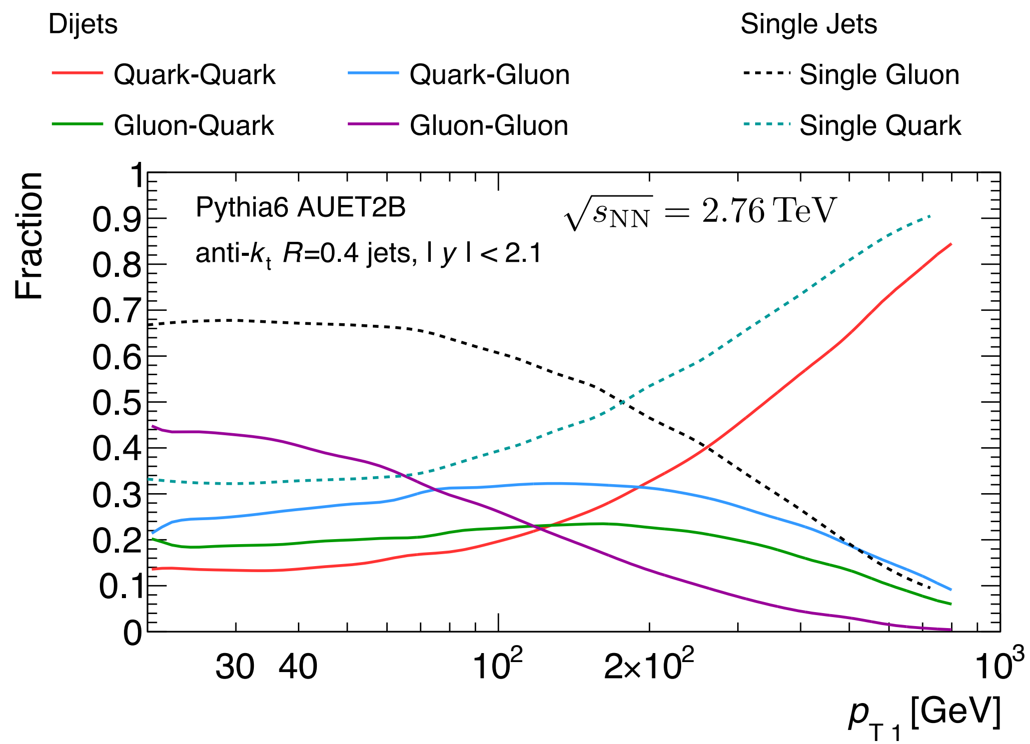


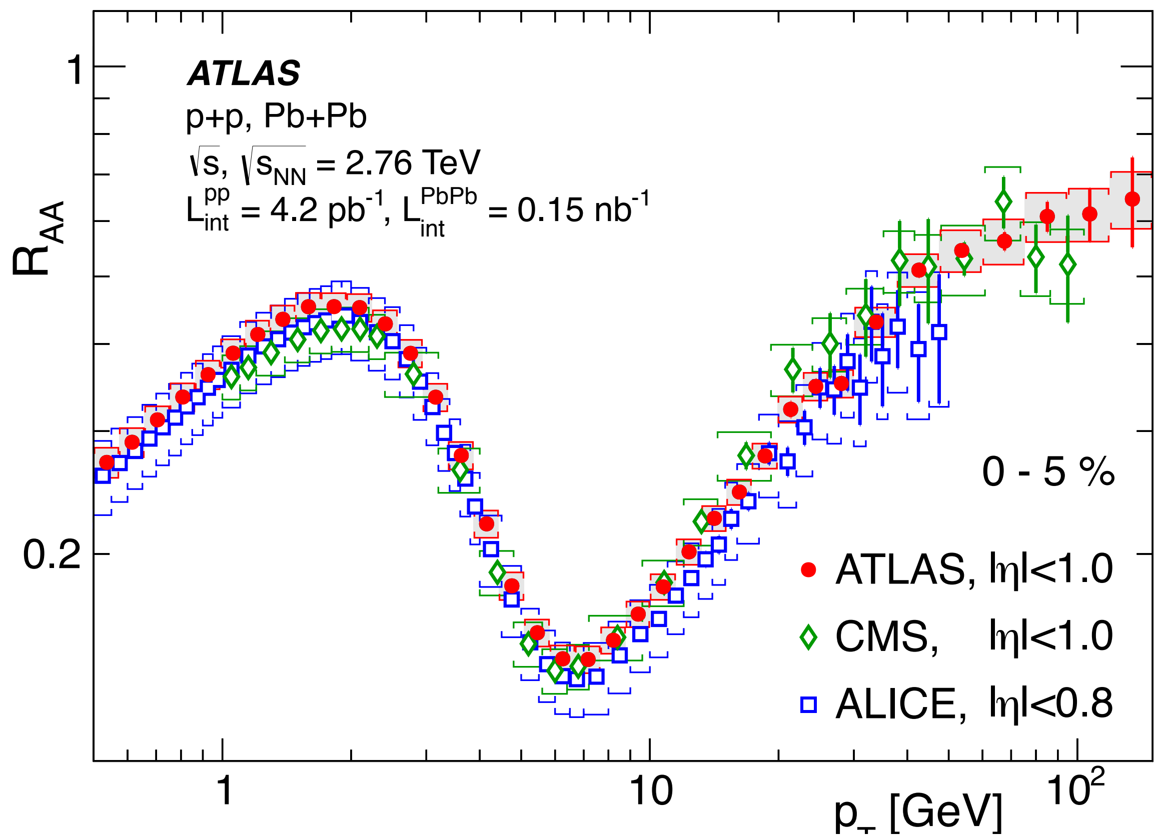
Figure from 1504.05169 [hep-ph]



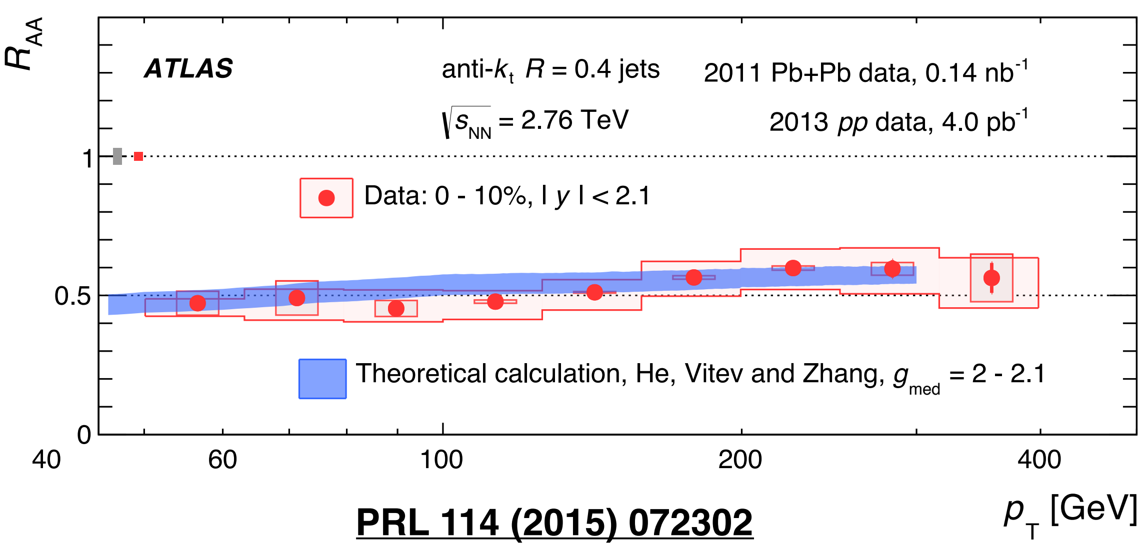
- **At fixed hadron p_T, expect different mixture of *q/g* than for inclusive jets**

Single Jet Observables: p_T Dependence

JHEP09 (2015) 050



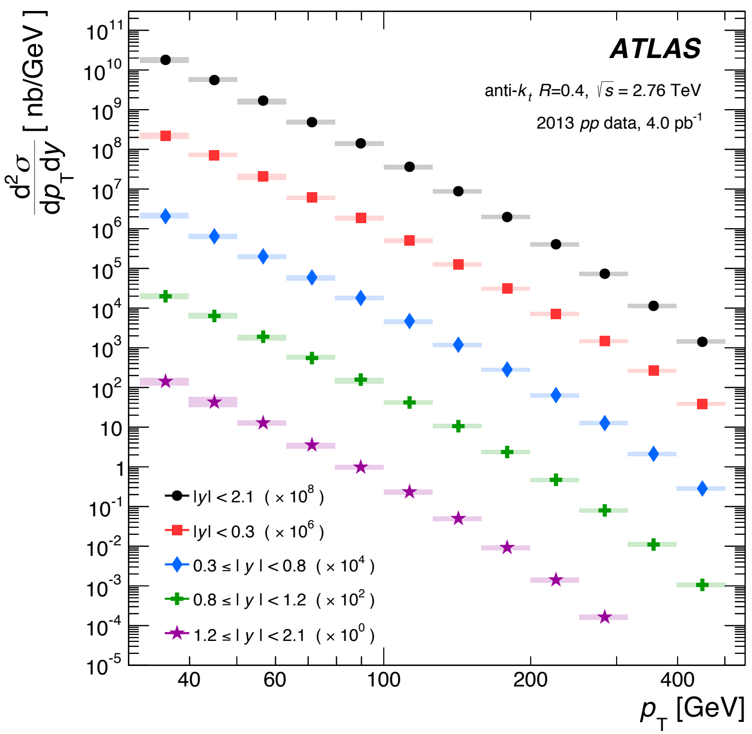
- R_{AA} **for charged hadrons**
- **Can see more of flattening trend in latest ATLAS measurement**

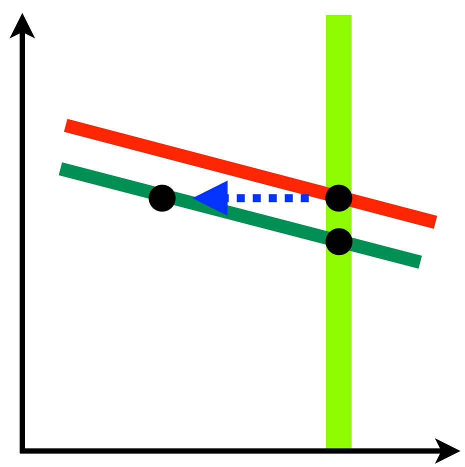


PRL 114 (2015) 072302

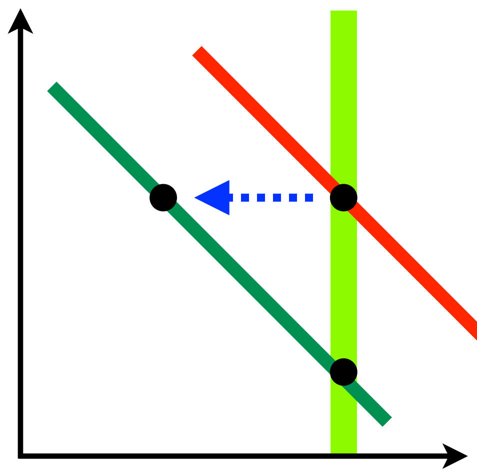
- **Qualitatively similar to flatness observed in jet** R_{AA}

Single Jet Observables: Rapidity Dependence





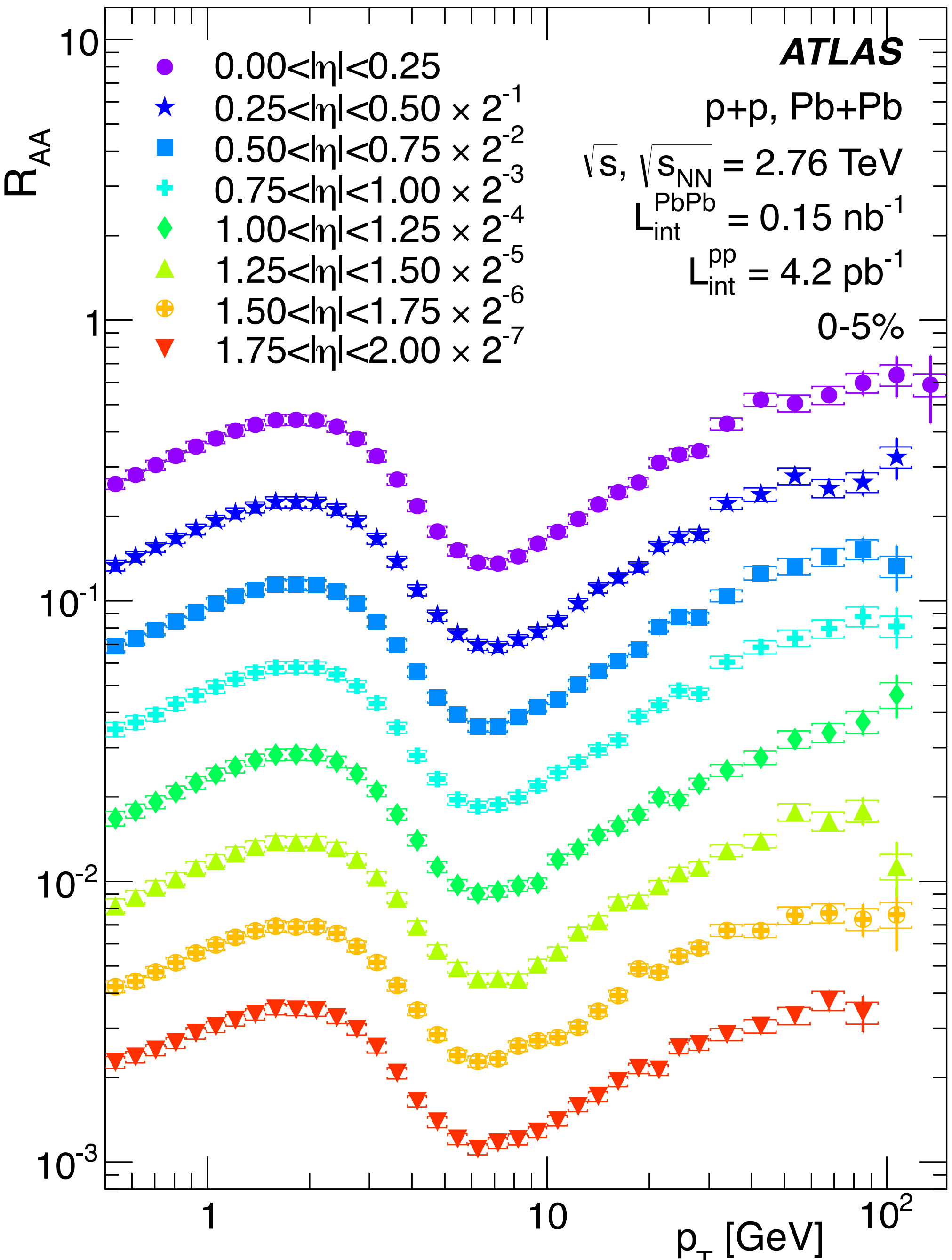
Mid-rapidity



forward rapidity

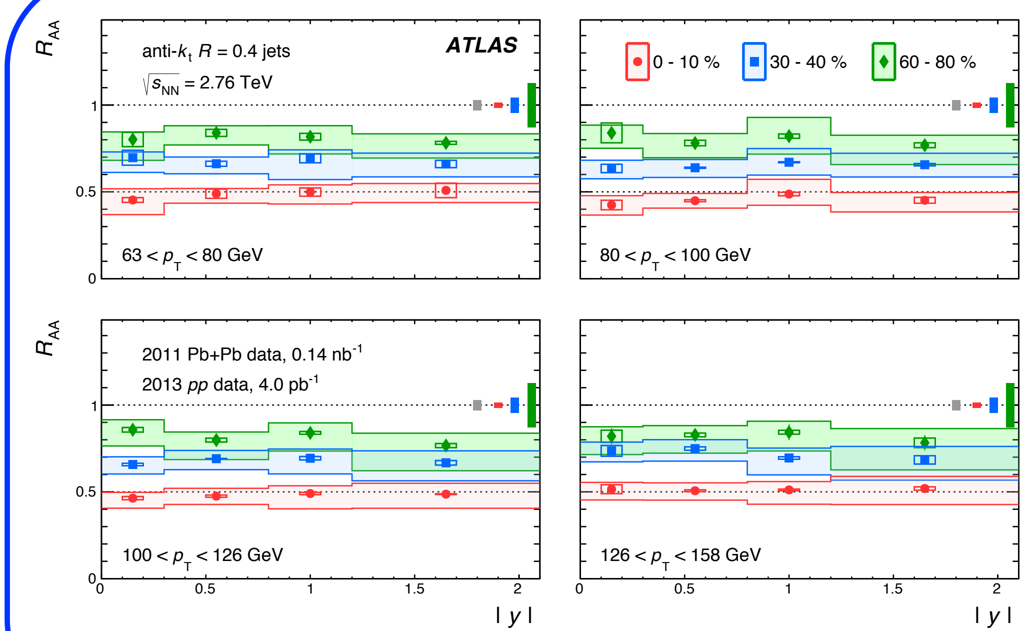
- Increasing rapidity results in a steeper production spectrum (lower R_{AA} at fixed energy loss)
- But higher fraction of quark jets (lower energy loss, higher RAA for fixed spectral slope)

Single Jet Observables: Rapidity Dependence



JHEP09 (2015) 050

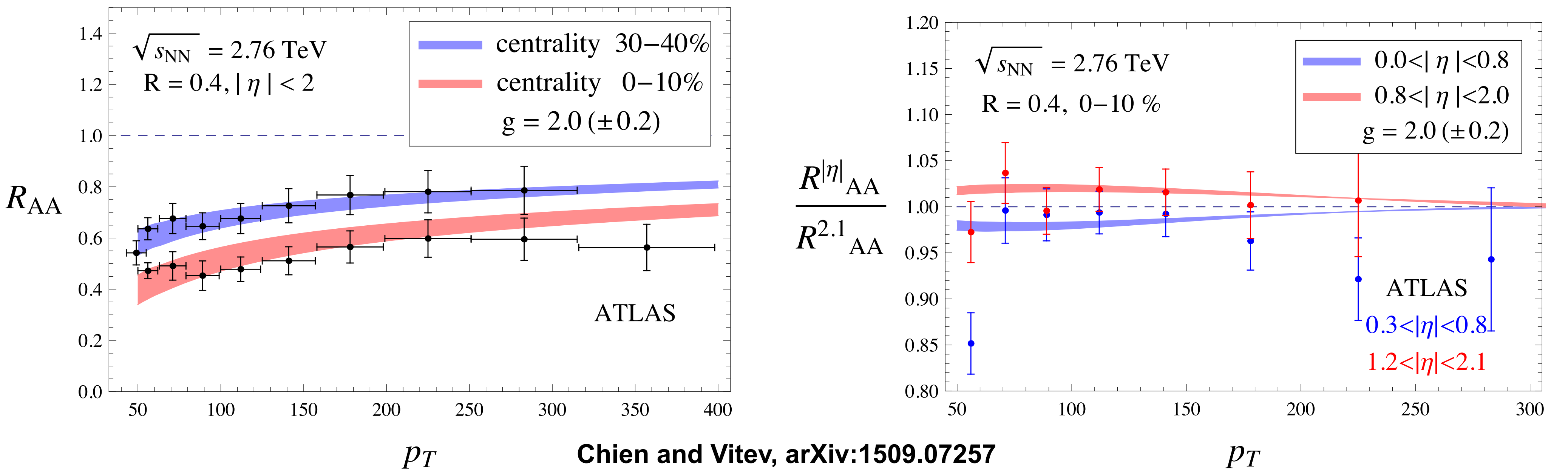
- **Neither shows large variation with rapidity suggestion effects mostly cancel**



PRL 114 (2015) 072302

Single Jet Observables: Rapidity Dependence

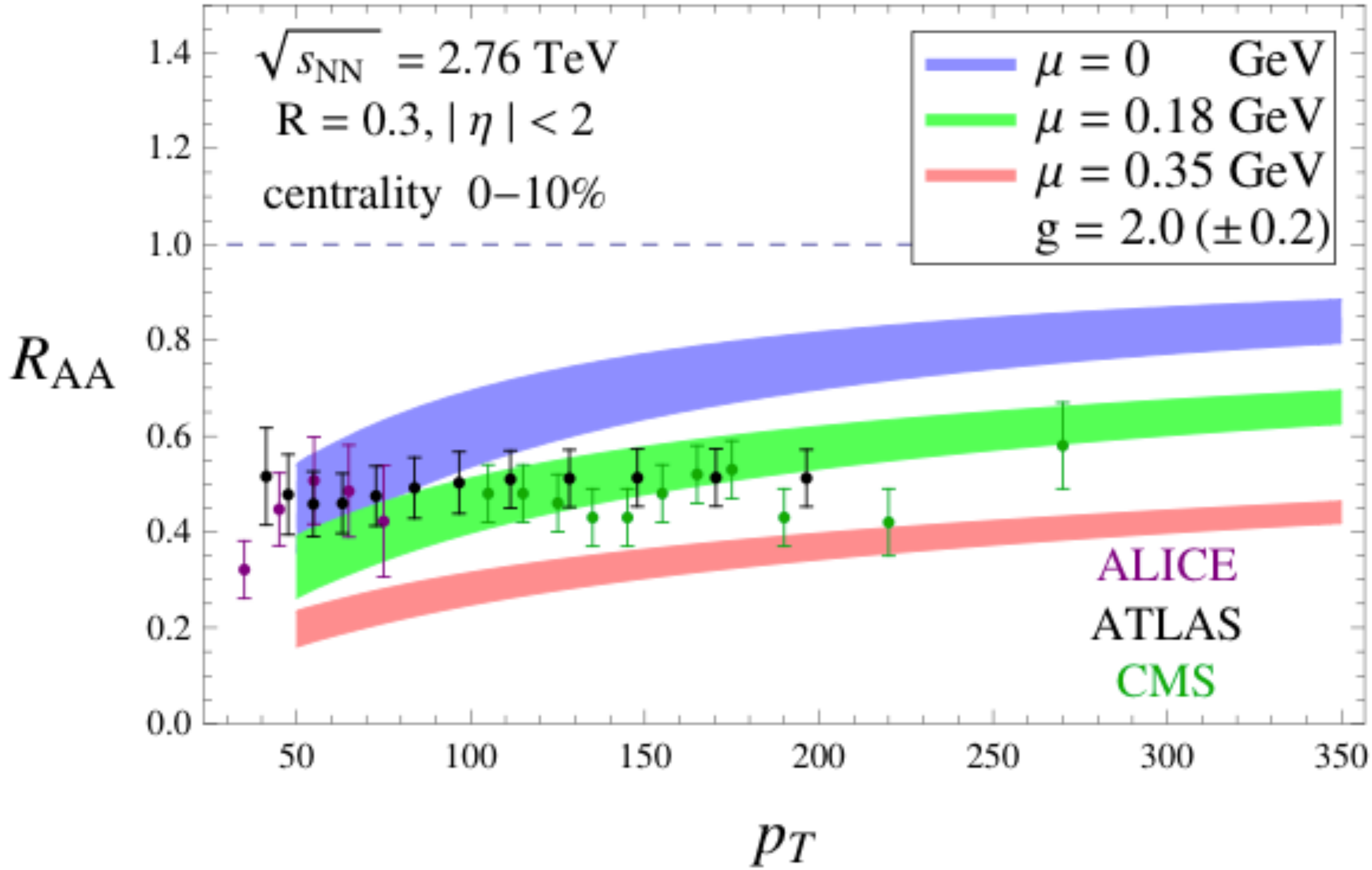
- p_T, centrality and y dependence of R_{AA} well described by recent calculations



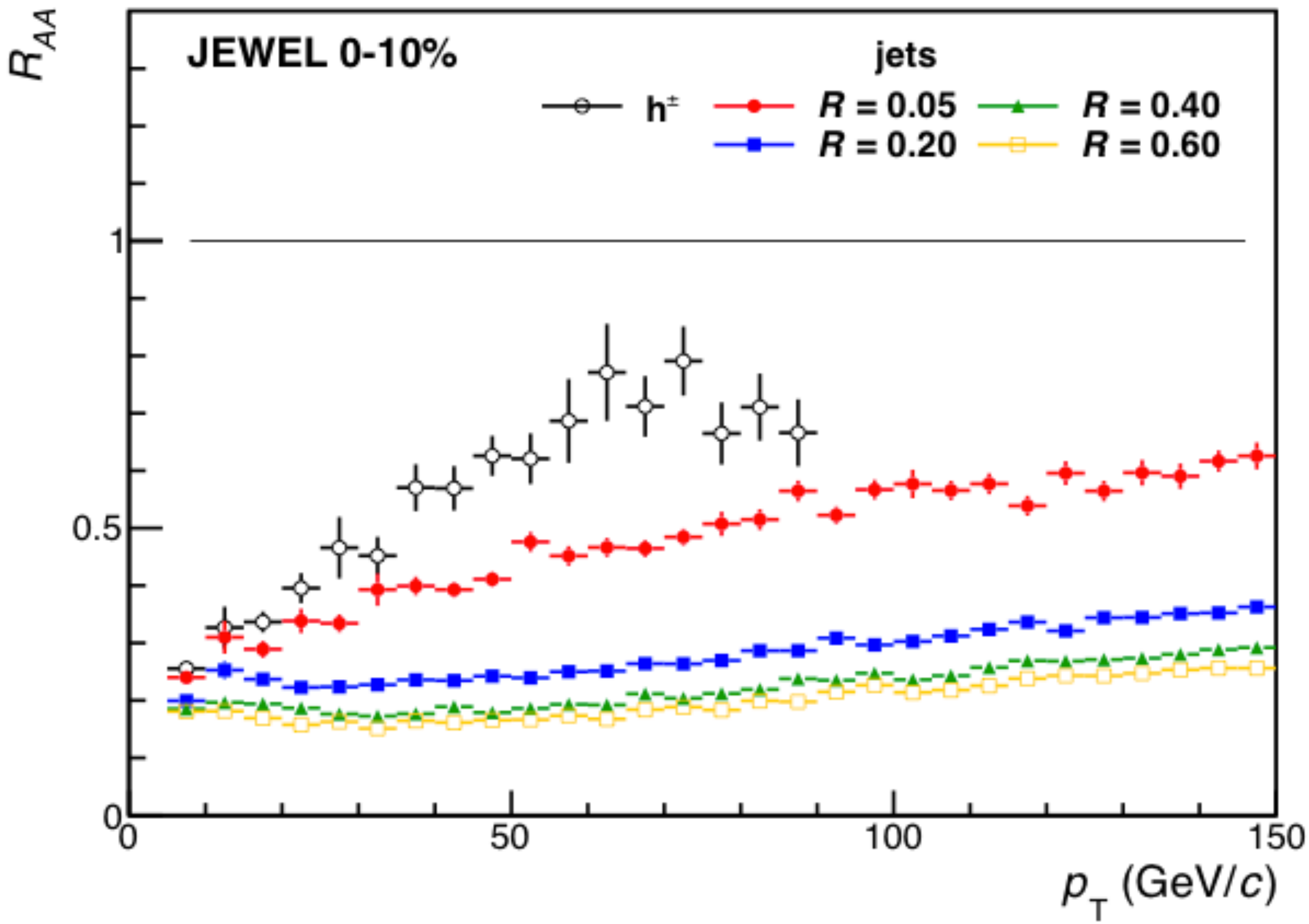
Chien and Vitev, arXiv:1509.07257

- R_{AA} larger at forward rapidity ⇒ increasing quark fraction wins out over increasing steepness of spectrum

Vitev, arXiv:1601.00015

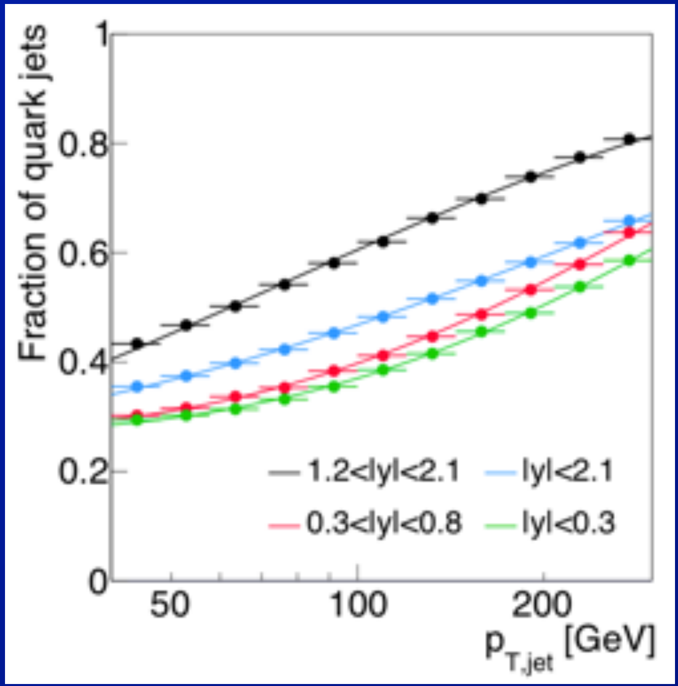


Van Leeuwen, arXiv:1511.06108

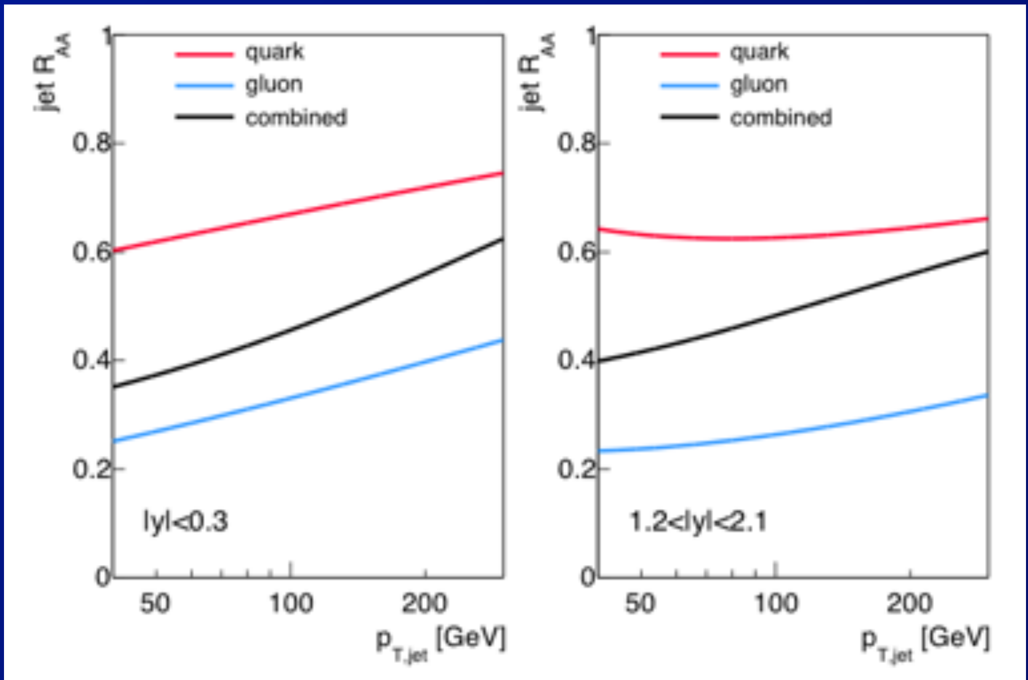


Importance of q/g fraction

PYTHIA8 AU2, CT10



Spousta, BAC Eur.Phys.J. C76 (2016)

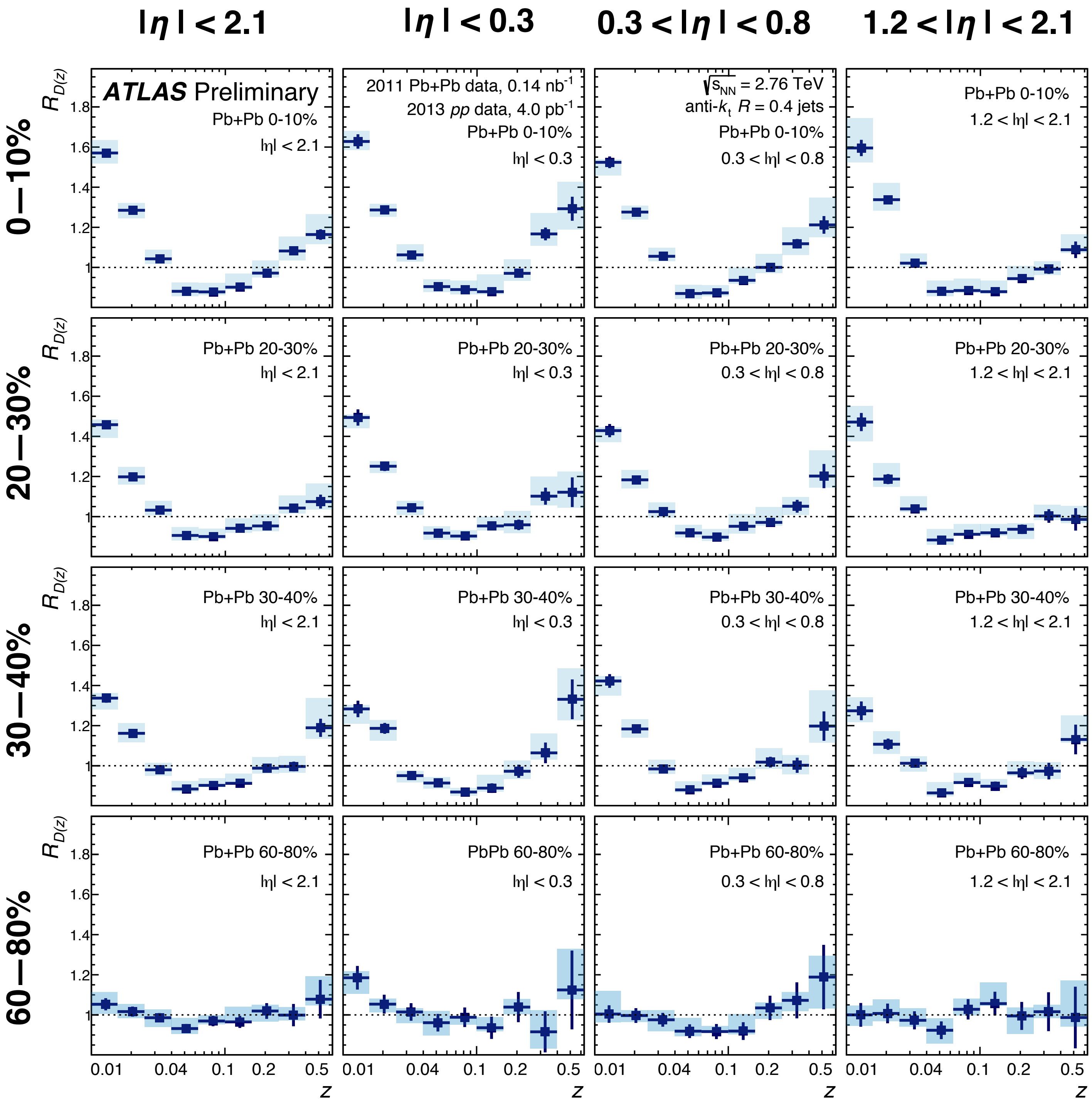


- "Toy++" quenching model:
  - pT dependence of R_{AA} at high p_T driven by variation in the quark fraction

    ⇒important to constrain q/g energy loss
- boson + jet helpful (much larger quark fraction)

  ⇒even jet R_{AA} in boson events

Jet Structure: Rapidity Dependence

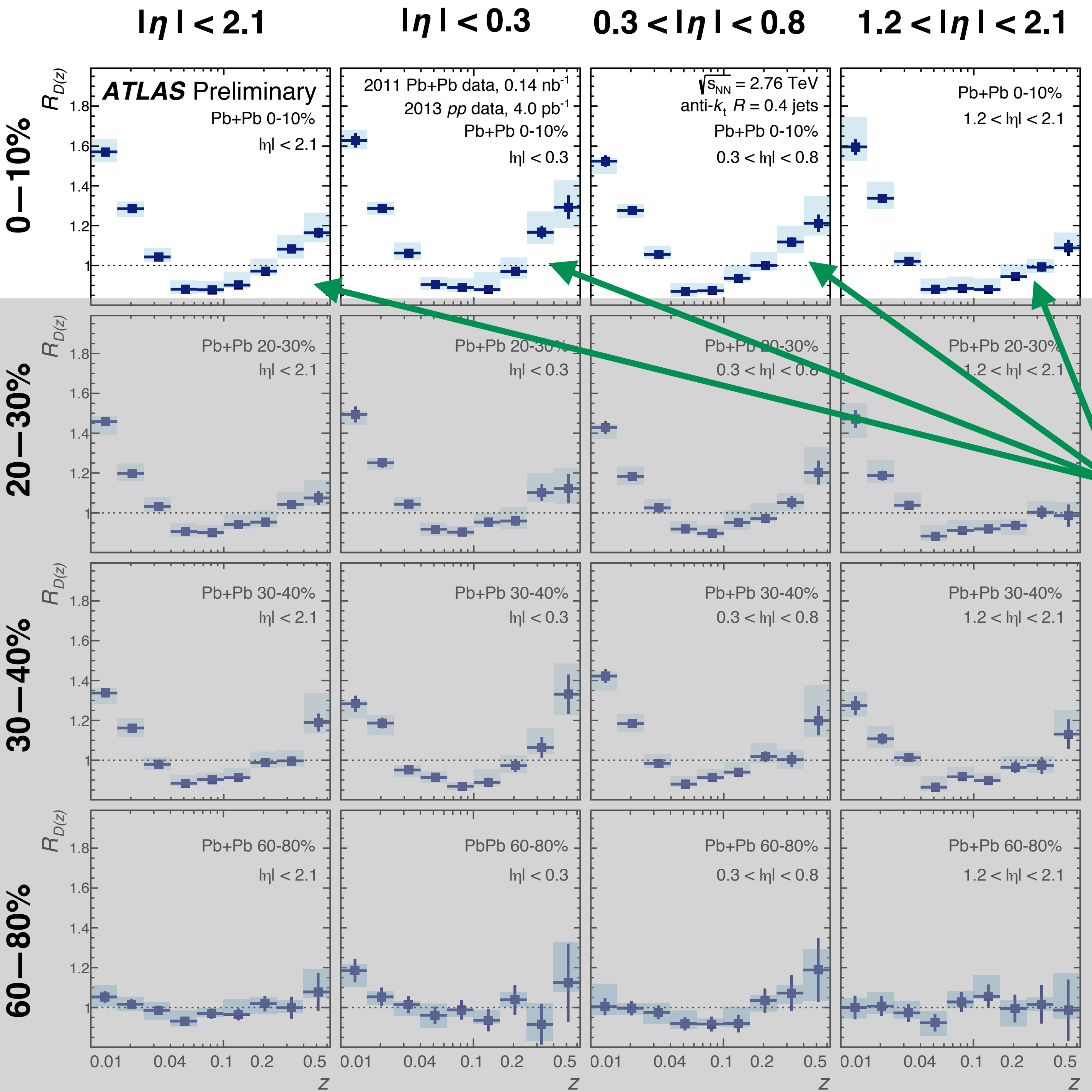


New fragmentation measurement

- **Includes *pp* reference using high stat. 2013 run**
  - ➡ **Significant improvement in ratios at high z**

ATLAS-CONF-2015-055

Jet Structure: Rapidity Dependence

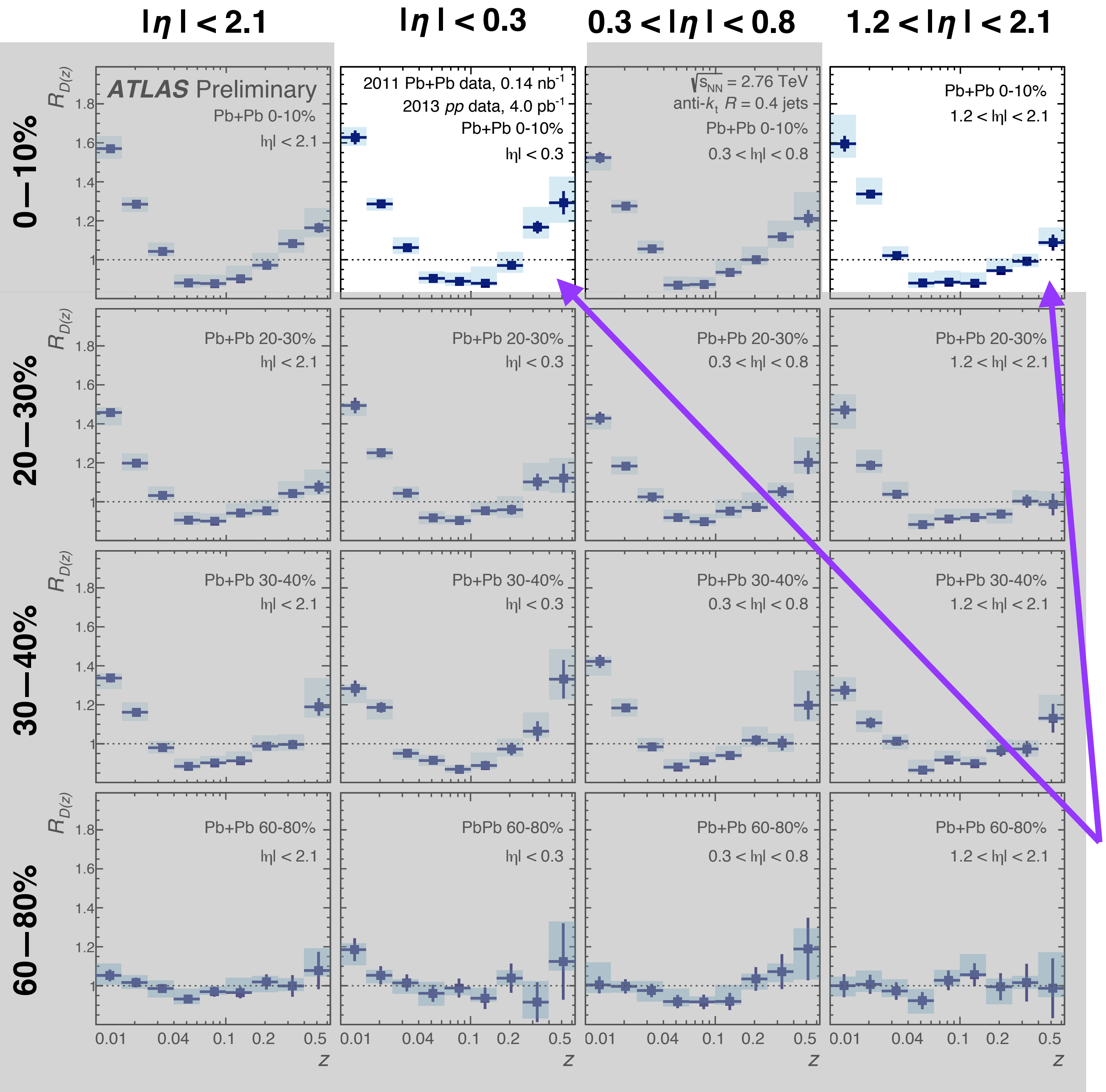


New fragmentation measurement

- **Includes *pp* reference using high stat. 2013 run**
  - ➡ **Significant improvement in ratios at high z**
- **Modifications at high *z* observed to be significant for first time**

ATLAS-CONF-2015-055

Jet Structure: Rapidity Dependence

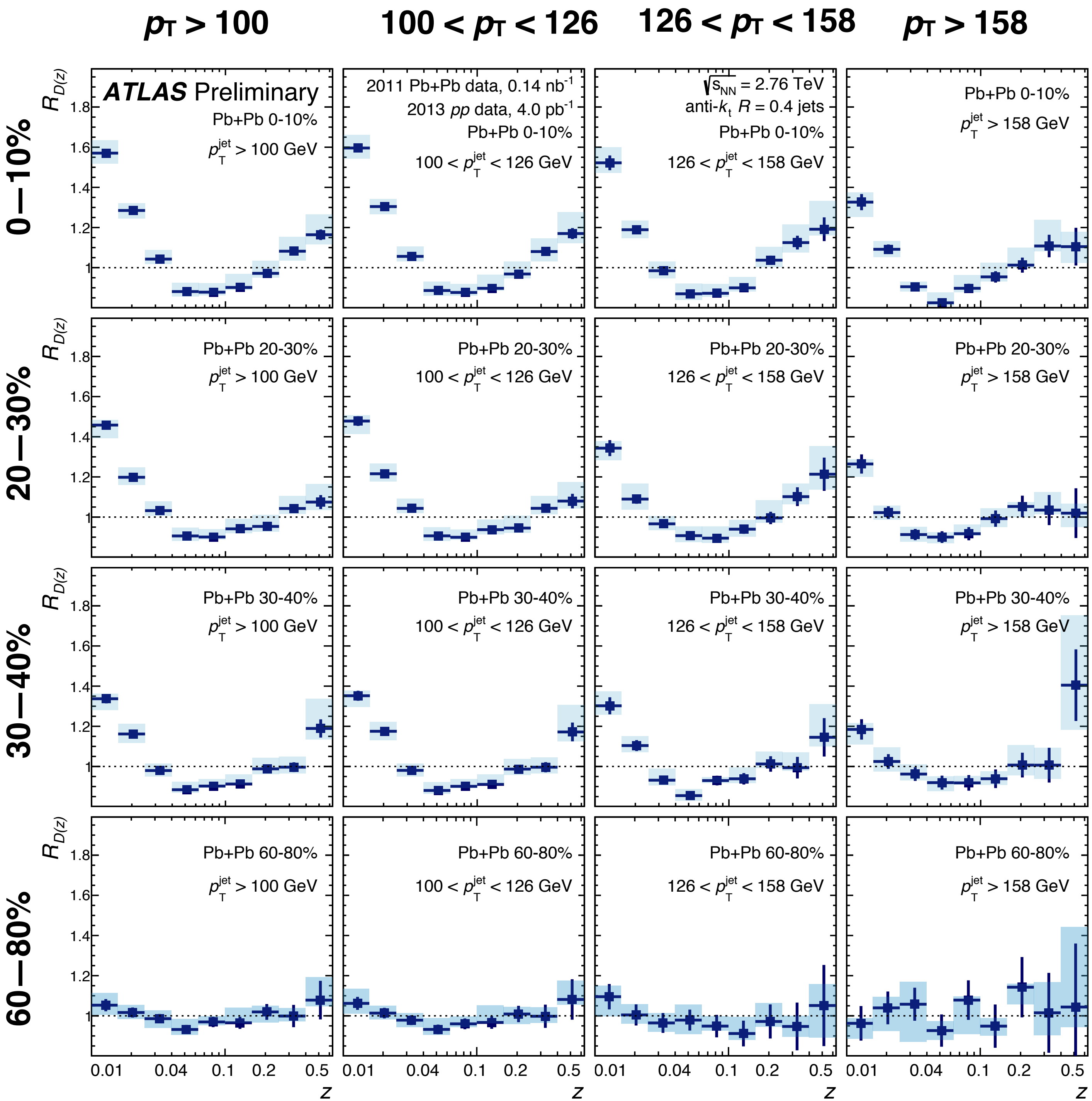


New fragmentation measurement

- Includes *pp* reference using high stat. 2013 run
  - ➡ Significant improvement in ratios at high z
- Modifications at high *z* observed to be significant for first time
- Jet p_T and η dependence
  - Unmodified distributions for quark and gluon jets very different
- Modifications at high *z* weaker at larger η
  - Higher quark fraction?

ATLAS-CONF-2015-055

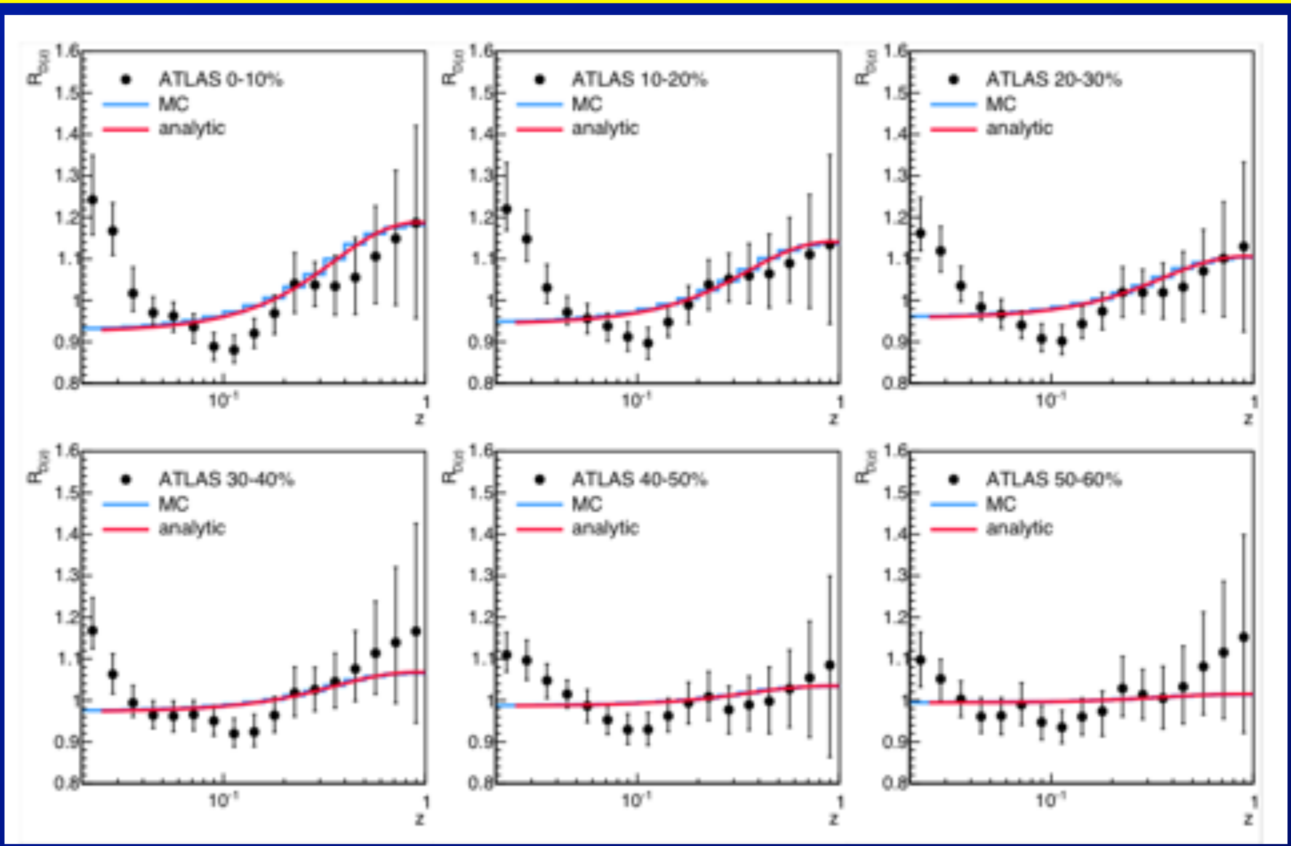
Jet structure : p_T dependence



- **Modifications at high z are less strong at larger p_T**

ATLAS-CONF-2015-055

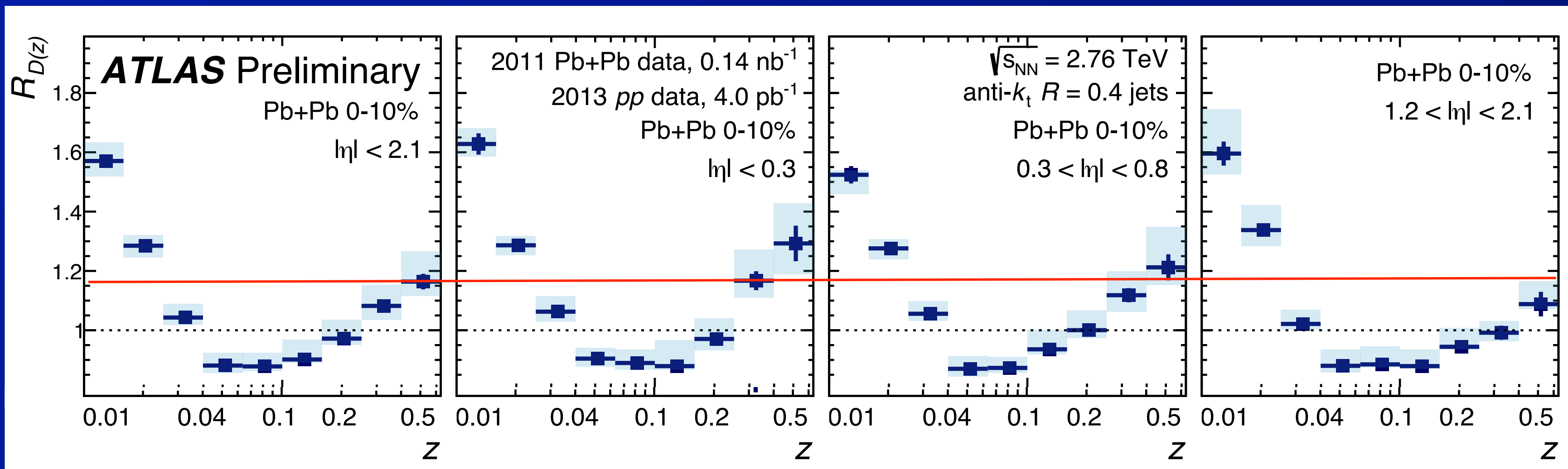
Importance of q/g fraction



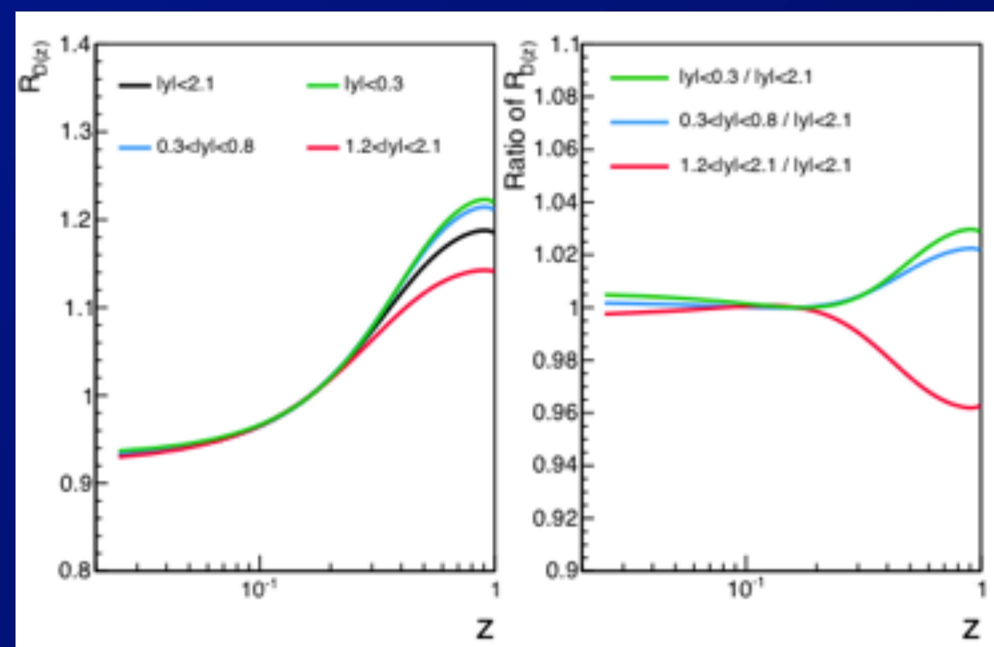
- Much of the modification of inclusive FF and its centrality dependence can be explained by change in q/g fraction due to energy loss

  ⇒"trivial" effect that must be present and should be accounted for in any calculation

q/g fraction: eta dependence

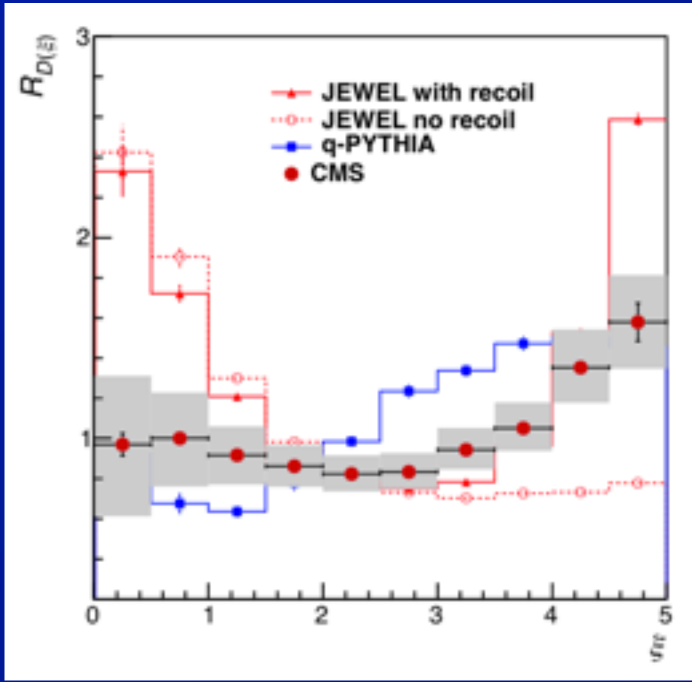


- **Hints that expected η dependence due to q/g fraction is seen in data**
  - ⇒But, properly, need to account for correlated syst. uncertainties in data.

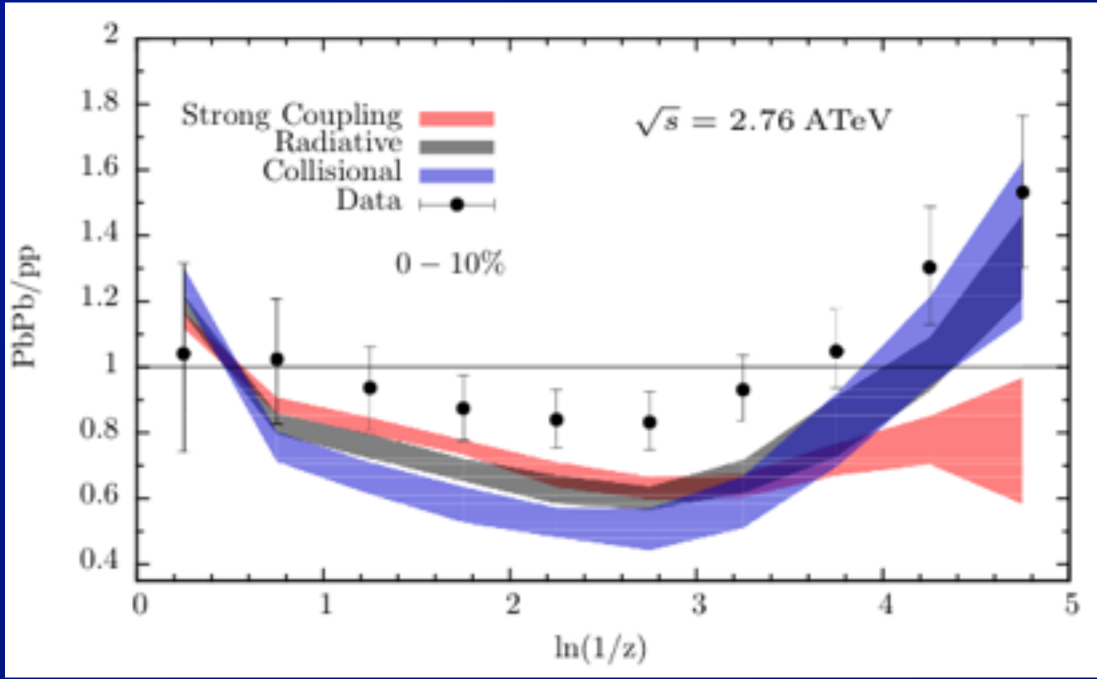


Low-z excess

Van Leeuwen, arXiv: 1511.06108



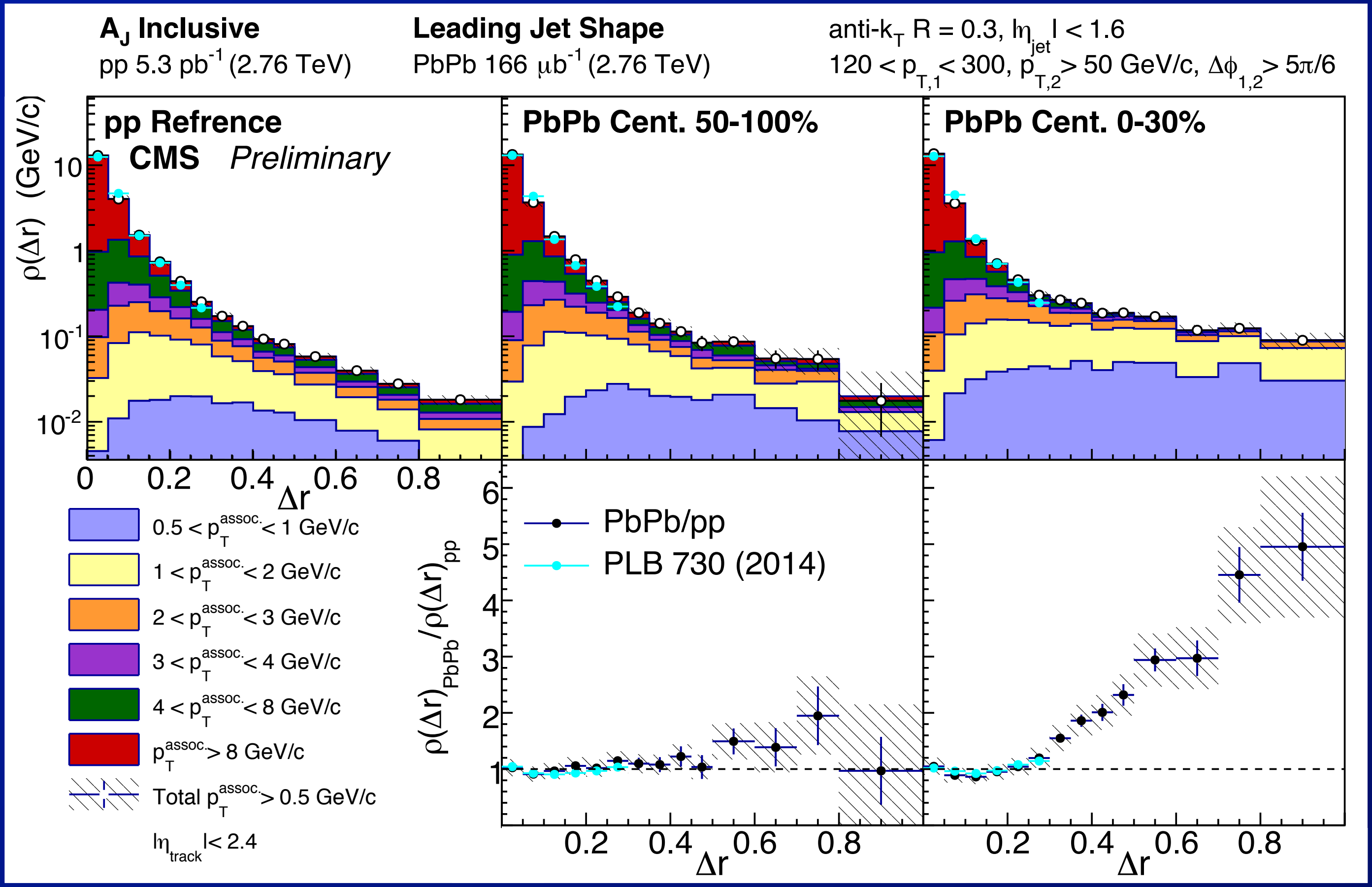
Casalderrey-Solana et al, JHEP 1603 (2016) 053



- Analysis using JEWEL suggests the low-z excess due to collisional recoils.
- Hybrid strong coupling model does not produce low-z excess when medium response not included.

  ⇒Hugely important if there is a kinematic region where medium response is “separable”.

Fragmentation angular distribution

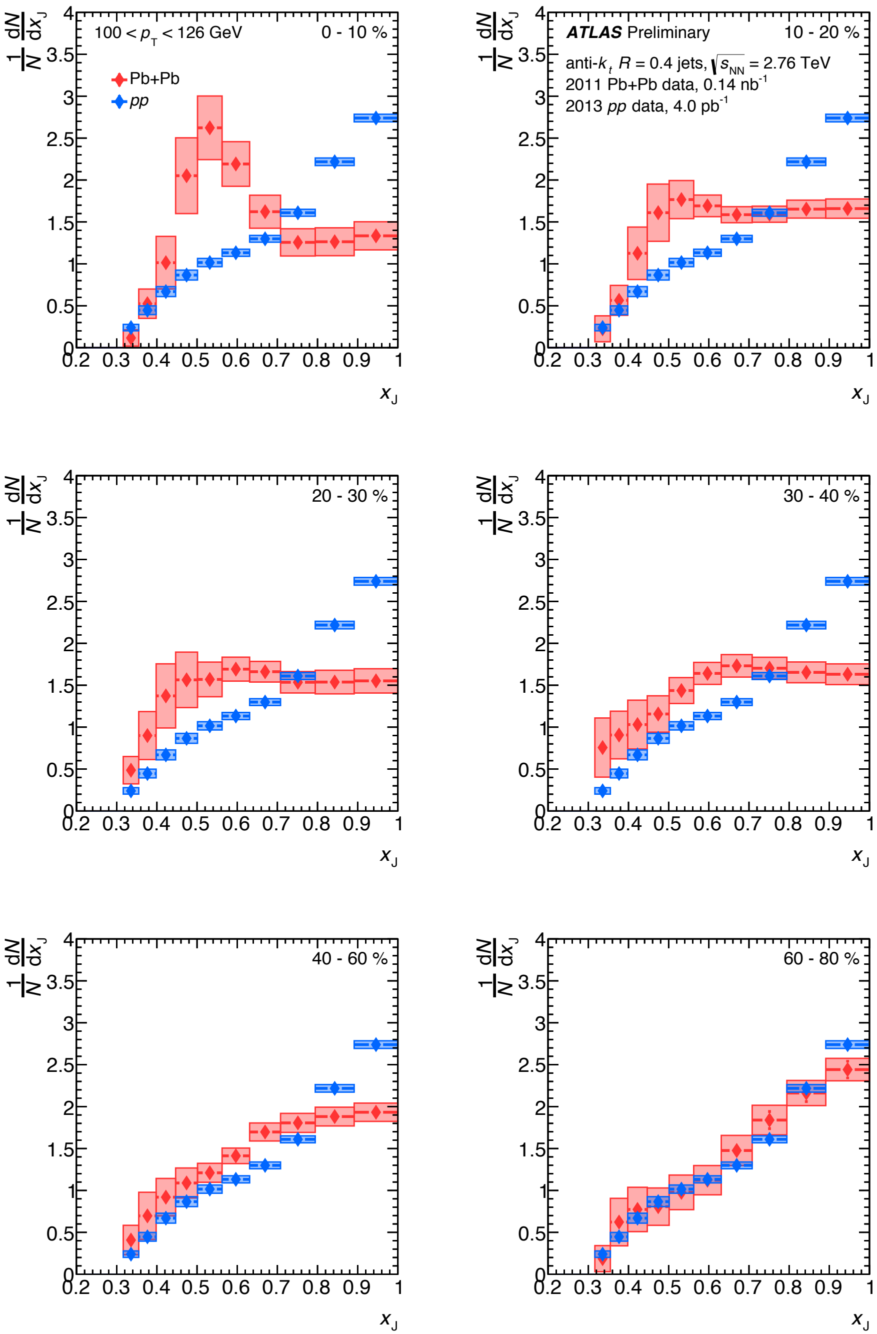


- **This measurement is crucial**
  - **Particularly need to see the ratios for different p_T.**
    - ⇒ **separate regions of low-z excess, depletion**
    - ⇒ **but, also need to control for changes in q/g ratio**

Wednesday, April 13, 16

Jet Energy loss: Dijet asymmetry

$100 < p_{T1} < 126$ GeV, $x_J = p_{T2} / p_{T1}$



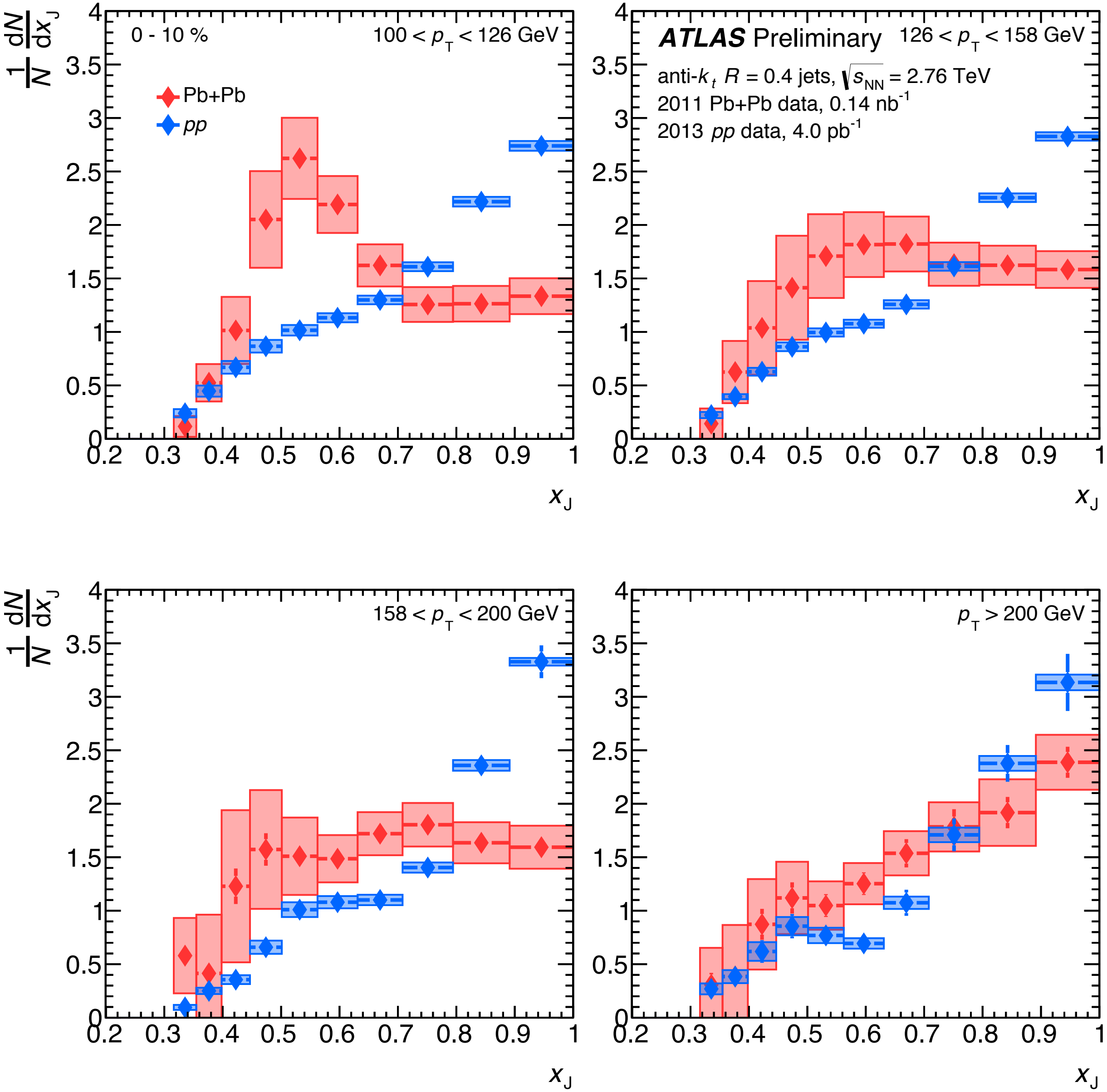
- <u>Fully unfolded</u> in two-dimensional p_{T2} - p_{T1} space and projected onto x_J
  - <u>Can be directly compared to theory</u>
- In pp collisions, most probable dijet configuration is x_J~1, balanced dijets
- In central Pb+Pb collisions most probable configuration for dijets is for one jet to have HALF as much energy as the other

➡ Qualitative change in dijet behavior general feature of central HI collisions

<u>ATLAS-CONF-2015-052</u>

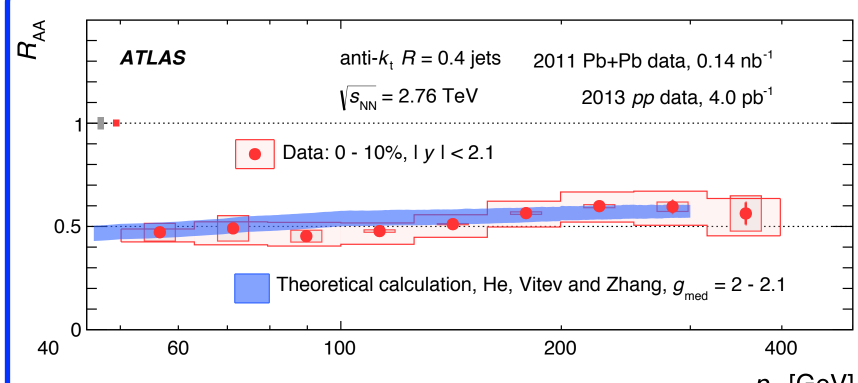
Dijets: p_{T1} and Possible Flavor Dependence

For dijets, *qq/gg/qg* composition of pairs changes with p_{T1}



ATLAS-CONF-2015-052

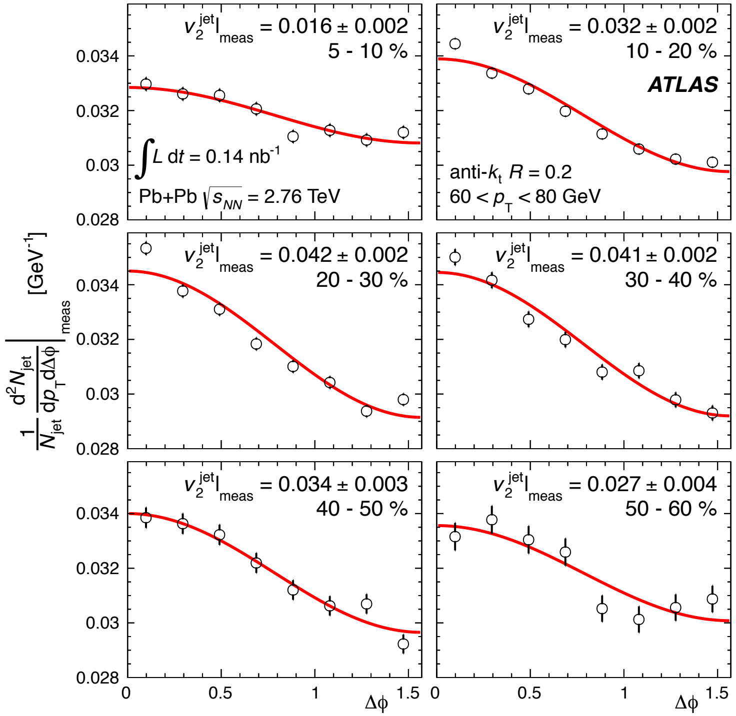
p_{T1} evolution more abrupt than for single jets, e.g. R_{AA} shows very weak p_T dependence



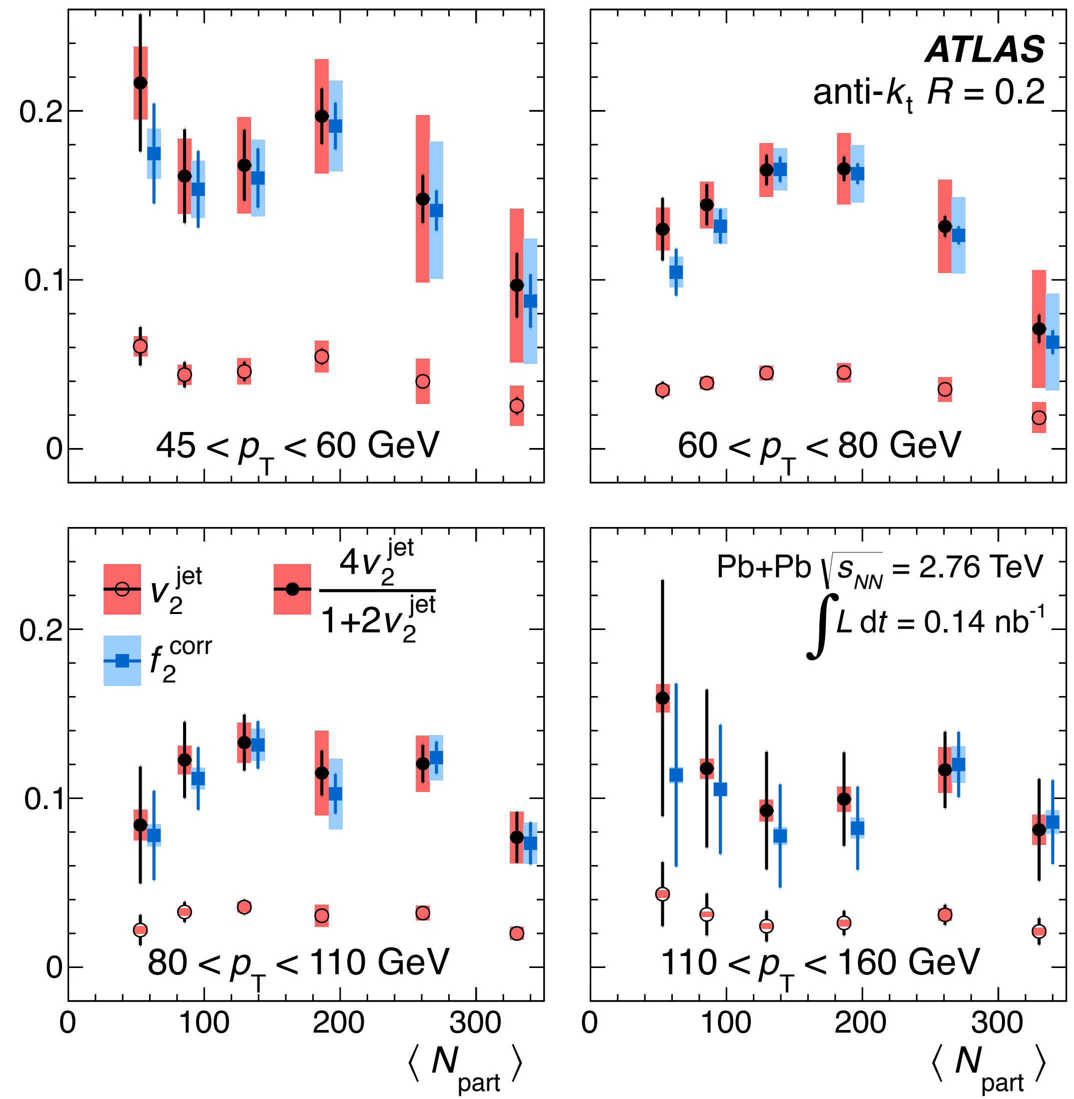
PRL 114 (2015) 072302

Much less modification at higher p_T

Single Jets : Geometry Dependence



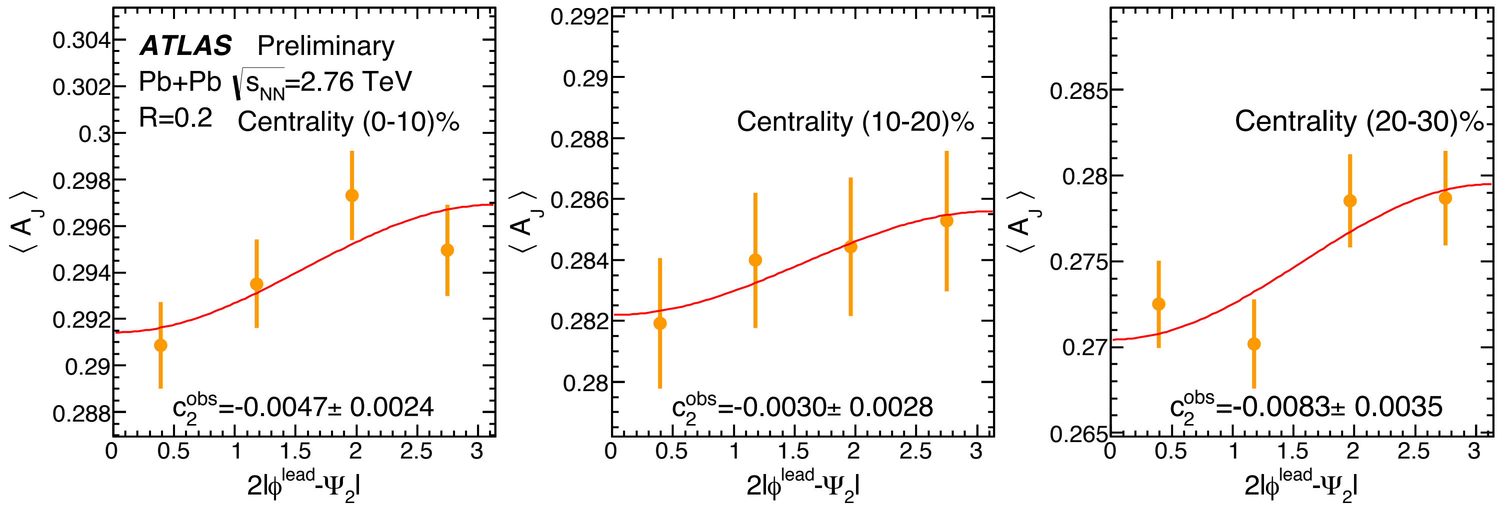
- **Jet yields observed to depend on angle wrt second order event plane : $\Delta\phi = \phi - \psi_2$**

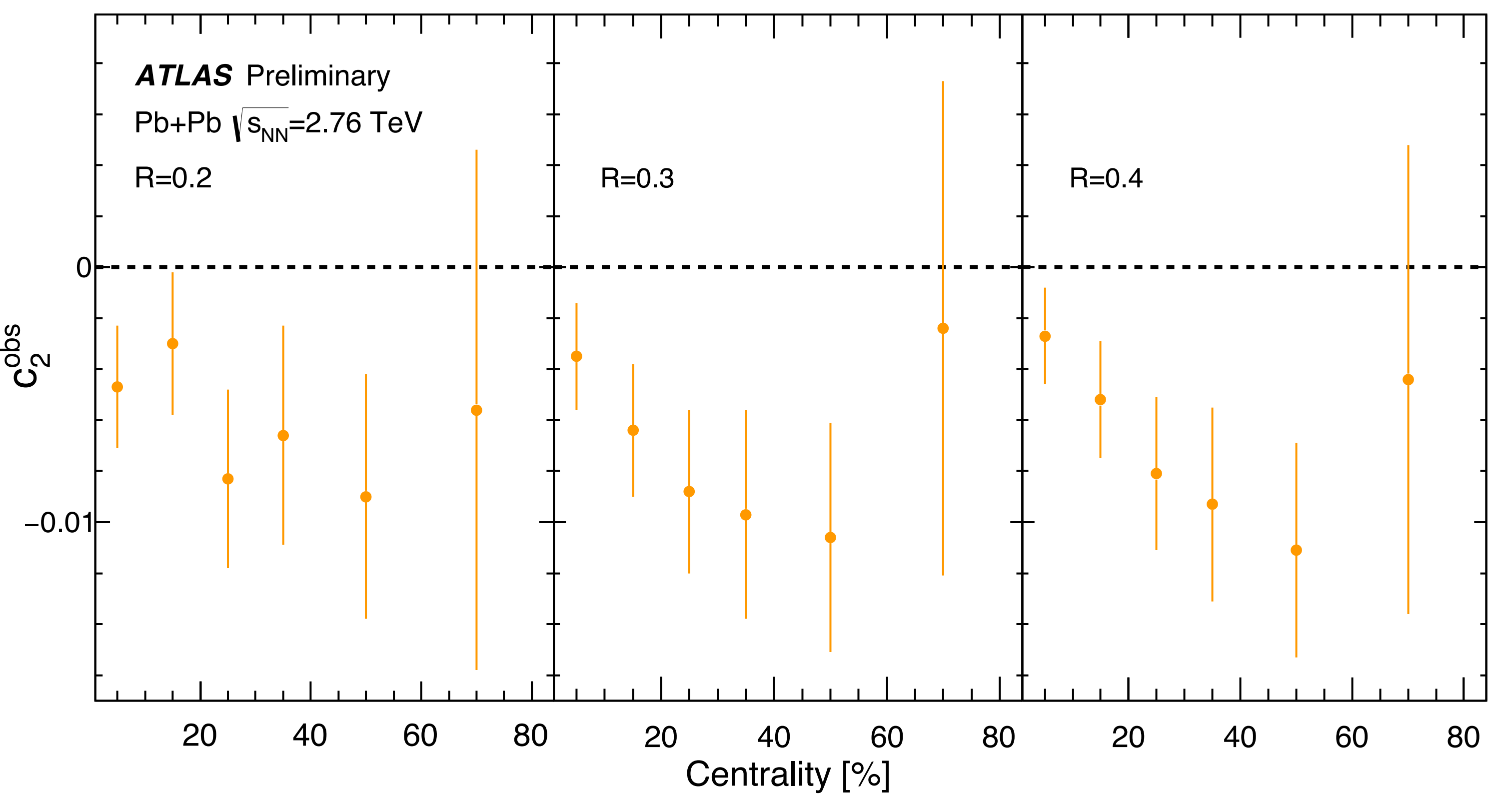


- **In/out-of-plane differences consistent with second harmonic modulation which is consistent w/ simple assumptions of L^2 E-loss and expanding medium**

Dijets: Geometry Dependence

$A_J = (p_{T1} - p_{T2}) / (p_{T1} + p_{T2})$ (not unfolded)





Very small, but significant anti-correlation between EP angle and $\langle A_J \rangle$

$\langle A_J \rangle$ smaller for dijets in the direction of EP which see shorter path lengths

Shows second harmonic modulation

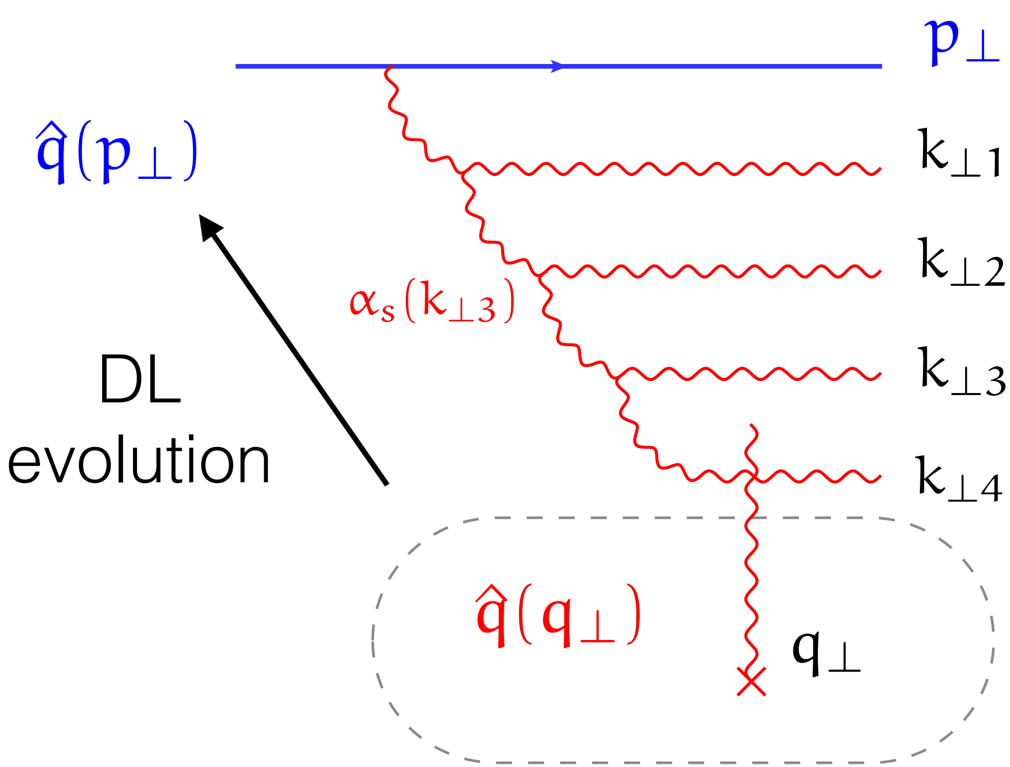
Constrains extent to which asymmetry determined by geometry

ATLAS-CONF-2015-021

Radiative Corrections to qhat

- Resummation of radiative corrections yields ***anomalous dimension for qhat***
- Implies anomalous dimension for path length dependence

$$q_\perp \sim m_D \ll k_{\perp 1} \ll \ldots \ll p_\perp \sim Q_s = \hat{q}L$$



$$\Delta E \sim L^{2+\gamma} \quad \text{with} \quad \gamma \equiv \sqrt{\frac{4\alpha_s N_c}{\pi}}$$

Diagram from Y. Mehtar-Tani's talk at QM15

- **Analysis predicts a path length dependence between pQCD radiative energy loss (L^2) and AdS strong coupling (L^3)**

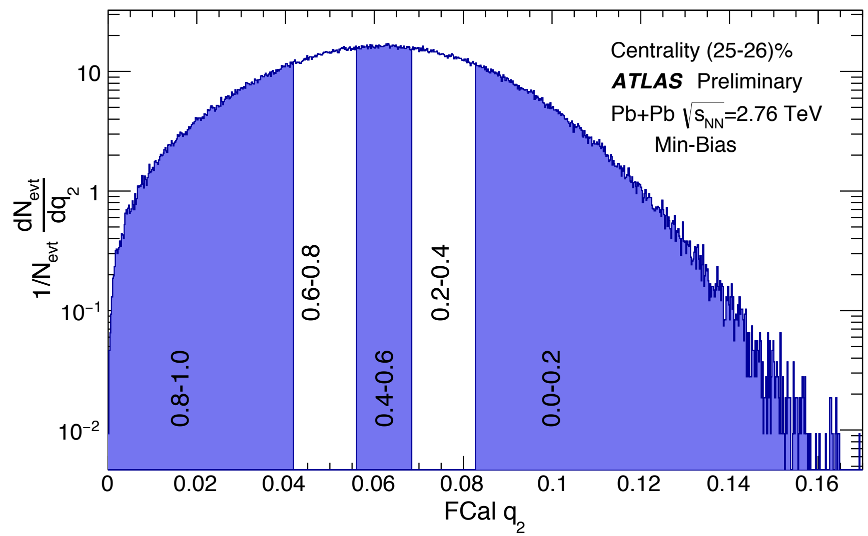
  ➡ **Tantalizing possibility to connect strong and weak coupling limits**

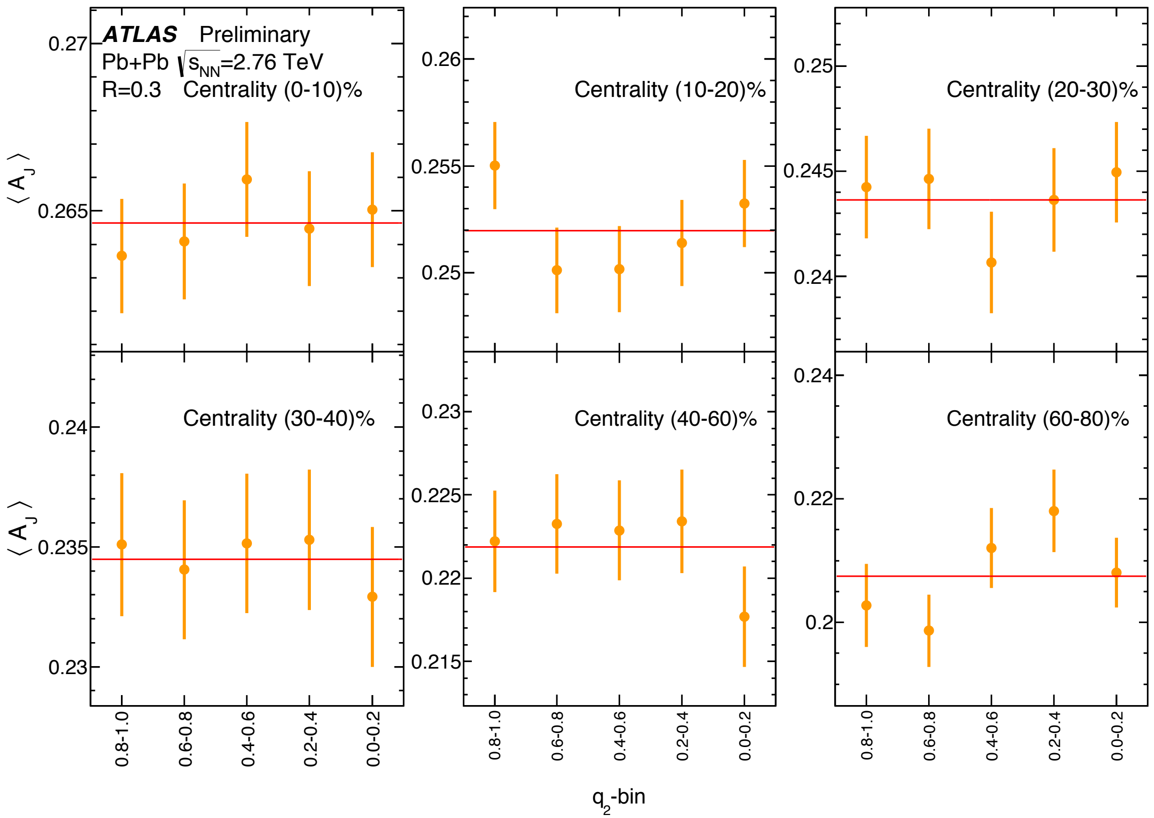
- **Can we observe effect of anomalous dimension through**
  - **More precise measurements?**
  - **Selection on kinematics to enhance contribution?**

Geometry and Jet Quenching : Next Steps

LHC Run 1 results showed improvments in determination of event-by-event geometry

Classify events both by centrality and ellipticity : $|q_2|$





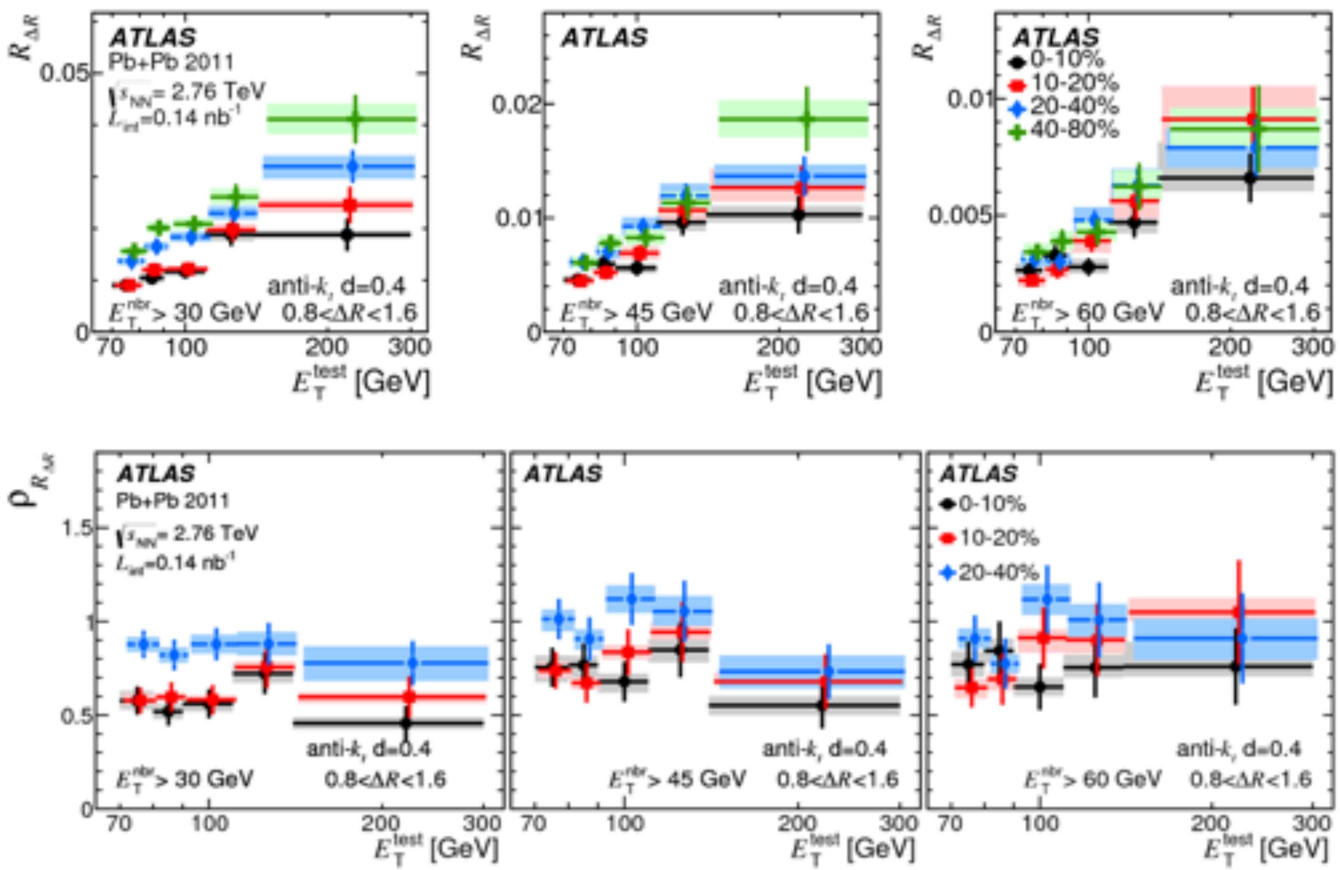
Running out of statistics for this in run 1…

$\langle A_J \rangle$ also has very small signal …

ATLAS-CONF-2015-021

Multi-jets in Heavy Ion Collisions

- LHC run 2 should benefit much higher rates of complicated radiation patterns
  - Nearby jets see similar path lengths and density fluctuations
  - Have correlated color structure
  - k_t / opening angle of splitting sets scale to probe medium



- First measurement of conditional yields of nearby jets performed by ATLAS could benefit hugely/be expanded
- Conditional yields are suppressed in central collisions

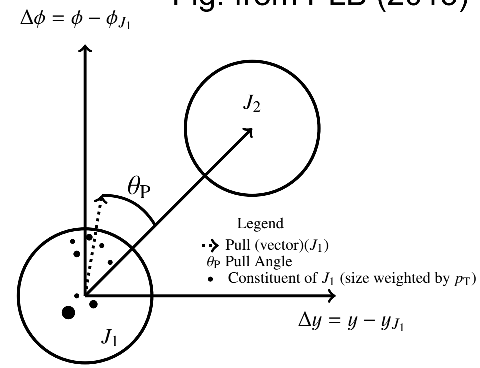
Summary

- There has been significant recent theoretical progress -- reason for optimism.
  - However, we still can't claim to "understand" even the most basic jet measurements (yet).
  - Important to account for "trivial" effects
    - ⇒Such as q/g changes due to quenching
- Specific issues:
  - low-z fragmentation excess an opportunity?
    - ⇒Recoil/medium feedback?
  - role of flavor, geometry vs fluctuations in dijets
    - ⇒Implications of p_T dependence in ATLAS data?
    - ⇒dijet asymmetry vs $\Delta\varphi$
  - jet structure/mass/angular scale
    - ⇒clearly the next step, but small R an issue

Observing Coherence Effects with Jet Pull ?

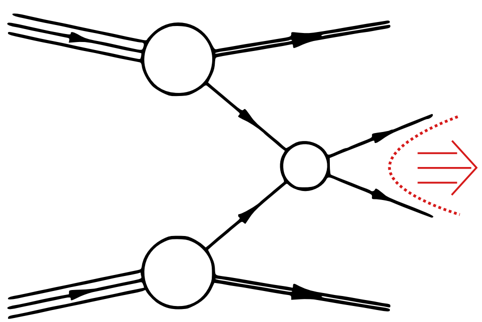
- **Observable sensitive to color flow: <u>jet pull vector</u>**
  $$\vec{v}_p^{\,J} = \sum_{i \in J} \frac{p_T^i |\vec{r}_i|}{p_T^J} \vec{r}_i.$$
  - **Example here is for distinguishing b bbar final states**

Fig. from PLB (2015) 475-493



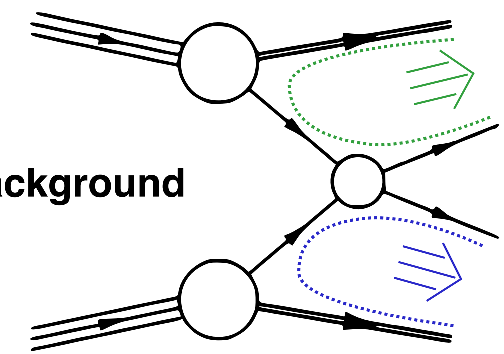
$$pp \to H \to b\bar{b}$$

Signal



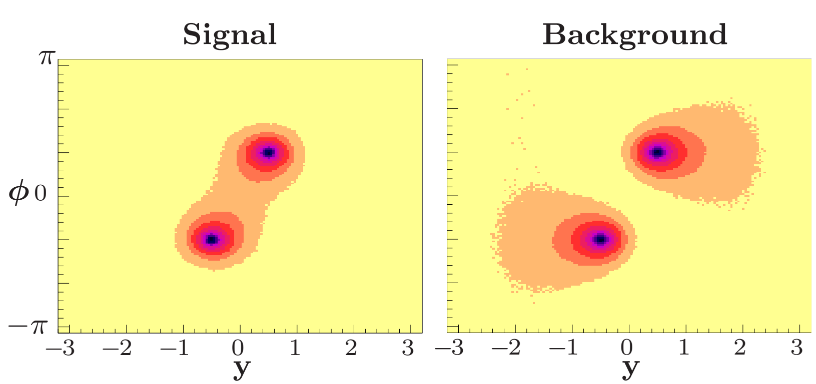
$$pp \to g \to b\bar{b}$$

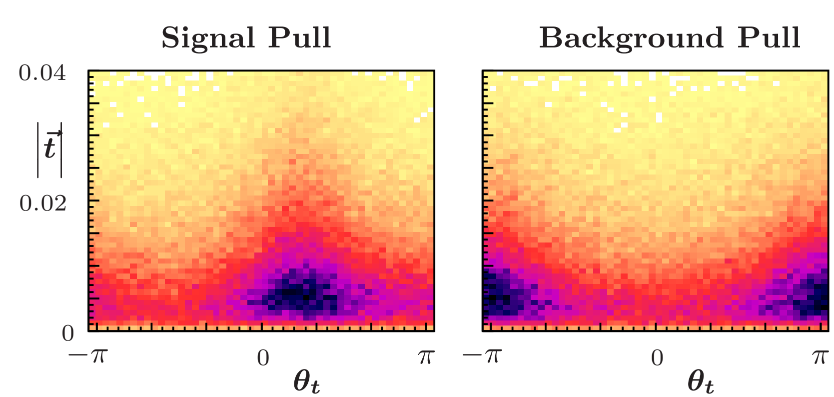
Background



Particle production on axis connecting jets

Color connection between jet and beam remnants





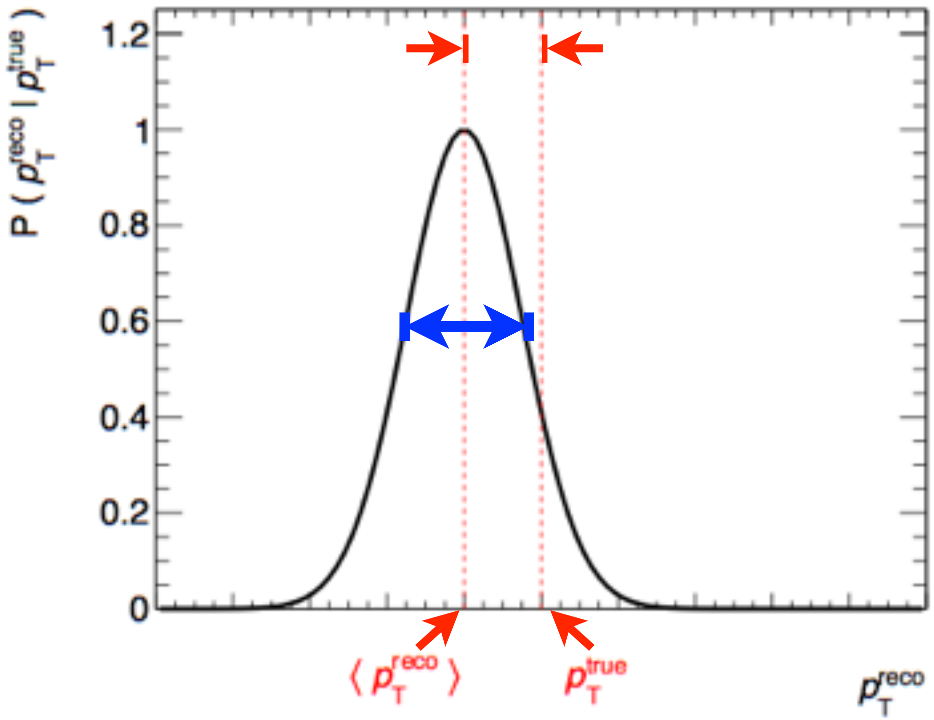
Gallicchio and Schwartz, Phys.Rev.Lett. 105 (2010) 022001

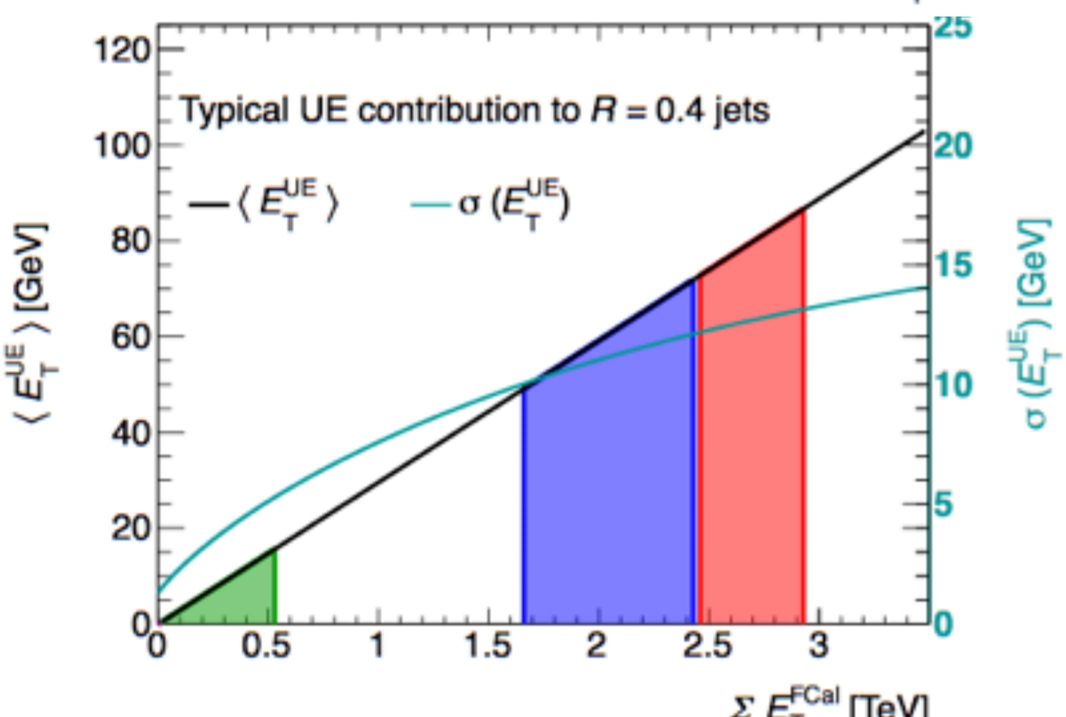
Summary

- See stronger quenching effects in kinematic regions where they are expected from underlying flavor fractions
  - Aspects of this puzzle (e.g. R_{AA}) already well described by theoretical calculations
- Needs full theoretical treatment to sort this out
  - Can be improved using new experimental results
    - Updated NPDF input from LHC measurements
    - Comparisons to unfolded x_J distributions ⇒ additional benchmark
- Flavor just one way of selecting jets with different parton showers
  - Measuring quenching observables for jets tagged by substructure properties could also address this
  - Multi-jets and observables sensitive to color flow also promising
  - Both get at role of decoherence in energy loss
- See geometric dependence consistent w/ L^2 path length dependence
  - Can we see deviations in Run 2?

Extras

Key Experimental Challenge: Jet Response





Jet energy scale (JES): shift in mean response

Jet energy resolution (JER): width of response distribution

Receive contributions both from UE and from detector

JES/JER convenient measures of response

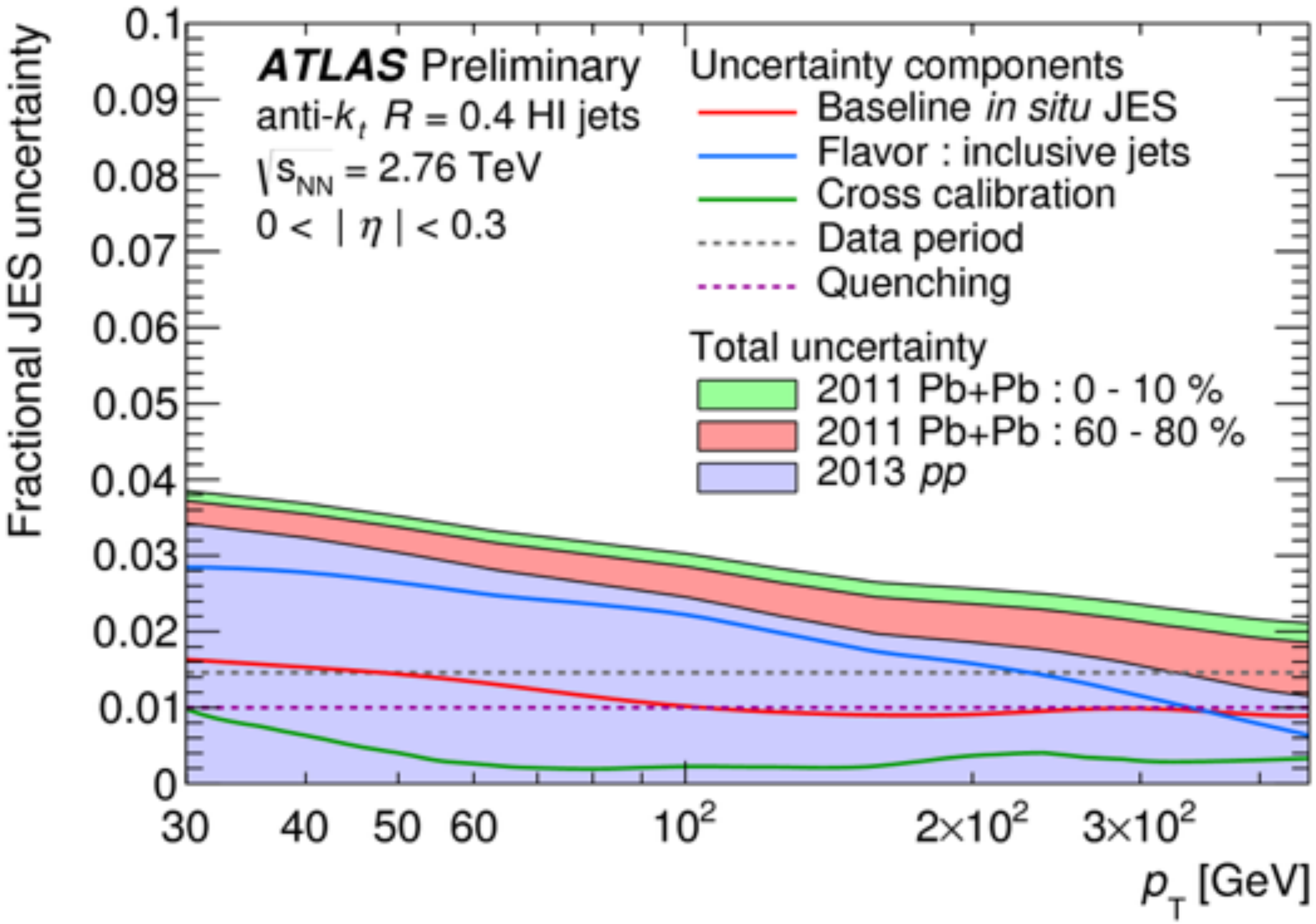
How well known they are often dominant systematic

In ATLAS use “data overlay” generator jets embedded in real HI events

UE contributions to jets described ~exactly

Key Experimental Challenge: Jet Response

Determine JES uncertainty on MC response through data-driven studies (*in situ* contribution)



"Data period" uncertainty arises from fact that *pp* an Pb+Pb data taken in different years and calorimeter response may have changed

Will not be present in run 2 since *pp* reference run was taken ~concurrently !

Residual contributions from fact that response is different for quark and gluon jets and may be different for quenched jets